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The On-Site Costs of Soil Erosion in Mali

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ABSTRACT

Land degradation in the Sahelian countries of West Africa is widely perceived as a critical threat to economic development. Some studies have quantified the extent of physical decline locally but few have attempted to determine its economic impact. There is some evidence, however, that current rates of depletion of Sahelian land resources may be excessive from an economic perspective, due to insecurity of land tenure and poorly developed capital markets.

This paper attempts to evaluate the gross on-site costs of soil erosion in Mali, a nation in which subsistence farming accounts for about one-fifth of national income. Mean local rates of soil erosion by rainfall are estimated and mapped using data derived from a land resources atlas of Mali and the Universal Soil Loss Equation (USLE). The analysis concerns only cultivated land within a north-south swath of Mali, comprising roughly one third of the country's most productive agricultural areas. Average soil loss is estimated at 6.5 tons/ha/yr, with higher losses occurring in the South (maximum 31 tons/ha/yr).

Using a range of assumptions about the impact of erosion on crop yields, estimated rates of soil erosion on farm land imply average annual yield penalties in the study area between 2% and 10%. These losses are expressed in terms of foregone net farm income, using farm budgets recorded in Burkina Faso.

Estimates of foregone farm income are compared to the costs of a relatively inexpensive soil conservation technology (rock contour bunds). Areas are identified where such investment may be justified as shown by a higher level of estimated farm income foregone.

The report suggests that economic returns to agriculture will be overstated by conventional benefit-cost analysis. On an annual basis, and ignoring possible price effects, current net farm income foregone nationwide due to soil erosion is estimated at US$4.6 to $18.7 million. However, soil erosion in one season affects crop yields in each subsequent year, until the land is fallowed. Under conservative assumptions of a ten-year time horizon and a 10% discount rate, the present value of current and future net farm income foregone nationwide, due to one year of average soil loss, is estimated at US$31 to $123 million (4% to 16% of agricultural GDP).

For most of Mali's agricultural lands, there probably exist some cost-effective measures to reduce erosion losses. We must distinguish, however, between cost-effectiveness from a public and from a private perspective. If farmers do not already use basic soil conserving measures, it may be because they discount potential increased future yields at such a high rate that almost any present investment is uneconomic. This might be more effectively remedied by policy changes, such as formal recognition of indigenous land tenure systems which would increase access to formal credit, or relaxation of constraints on informal credit.

Because of the uncertainty of the underlying calculations, any policy and program prescriptions based on this research must be tentative. The study is perhaps best considered as an illustration of a method of evaluating land degradation, rather than as a definitive analysis with which to justify intervention. Hence the emphasis throughout is on methods of approximation and comparison.

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I. INTRODUCTION

In the Republic of Mali, ecological deterioration can be seen in a variety of forms: reduced rainfall and river levels, loss of forests and pasture, reduced soil fertility, and loss of plant and animal species. For a nation largely dependent on agricultural production, these trends represent a potential threat to future economic welfare.

Some of these phenomena may be beyond human control. Others can be attributed to man's exploitation of the environment, and are susceptible to remedial action. What is required is to isolate 'man-made' environmental decline, determine whether it is excessive and, if so, identify useful options for public planners. An important step is to identify how different economic activities affect Mali's natural resources, and the extent to which these activities may undermine the nation's long-term productive capacity. The costs and benefits of feasible alternatives then should be specified. At local and national levels, such analysis lies at the heart of attempts to improve the management of renewable resources.

Conventional measures of economic activity often fail to reflect the negative environmental impacts of production. At the project level, cost-benefit calculations may not incorporate indirect environmental effects. At the macro-economic level, national income accounting typically ignores the depletion of natural resource inputs, on which that income depends (Appendix C).

This paper attempts to fill the gap in economic accounting for one nation and one major natural resource - the soil in Mali. We try to put a value on the top soil "used up" in agricultural production. We use an indirect method (i.e., crop yield effects), because there is no open market for farm land in Mali. If there were data on the sale or leasing of agricultural land, we could infer the value of soil fertility by comparing the prices of plots which differed only in the extent of land degradation.

The analysis here provides only a gross estimate of the economic losses incurred by soil erosion. We lack the information needed to determine what portion of those losses should be considered excessive. In principle, one could calculate the marginal benefit and the marginal cost of soil conservation, per ton of soil, and determine optimal levels of depletion and investment. The available data do not justify such effort in this case. We do, however, compare the estimated gross cost of erosion to the cost of a relatively inexpensive soil conservation technology - rock contour bunds. This permits identification of areas where soil conservation might begin, i.e., where gross losses due to soil erosion exceed the cost of conservation.

We use estimated soil erosion, in tons per hectare per year, as a proxy for declining soil fertility. Moreover, we confine attention to soil loss on cultivated land. Hence we do not estimate erosion on fallow or rangelands, nor its impact on livestock or woodland productivity. Finally, because we consider only the on-site costs of soil erosion, we ignore the negative (or positive) effects of siltation on floodplain agriculture, river navigation, irrigation networks, and fisheries. This is not to say that such impacts do not merit study.

Most of the data used here are derived from an atlas of Mali's land and water resources, prepared from satellite images, by Tippetts, Abbett, McCarthy, and Stratton (TAMS 1983). Using a geographic information system, we have digitized the maps contained in the atlas. This allows us to identify 1,281 "map units," each characterized by a unique combination of surface area, soil type, topography, rainfall, and land use. These characteristics are translated into the five variables of the Universal Soil Loss Equation (USLE), based on parameter values estimated empirically by previous researchers in West Africa. We calculate the average annual rate of soil loss on farm land for each map unit. The result is depicted graphically in Appendix A.1, in maps of the geographical distribution of estimated soil loss on farm land in the study area.

The method used to value soil loss is based on a model developed for an unpublished study of soil erosion on Java (Magrath & Arens 1987), described in Appendix C. Our version links soil erosion to crop yields, using regression models developed by the International Institute for Tropical Agriculture (IITA), in Nigeria (Lal 1981). An alternative "replacement cost" approach to valuing soil losses is presented in Appendix B. The latter relates soil loss to declining chemical fertility, using models similar to ones developed for Zimbabwe (Stocking 1988). Chemical losses are converted to equivalent weights of commercial fertilizer, which are valued using recent world prices.

The original models from IITA estimated yield losses from cumulative soil loss, under continuous cultivation, relative to yields on newly cleared (uneroded) land. Available data on crop yields, however, do not distinguish between eroded and uneroded land. This study uses crop budgets published by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, Matlon & Fafchamps 1988). These budgets were derived from village farm land in Burkina Faso which had been continuously cultivated for about ten years, on the average. We assume that this land incurred soil loss in every year of cultivation, and thus apply the IITA models to calculate the percentage <u>increase</u> in yield that would be gained, in the tenth crop year, if no erosion took place in the preceding ninth crop year. Applying prices from the ICRISAT crop budgets, and correcting for changes in farmers' use of variable inputs, we derive the value of the yield foregone due to erosion.

This "loss" may be generalized across the study area, based on estimates of the density of farming in each map unit.

The method used to value soil loss is simple, partly because available data do not permit use of more sophisticated models, but also because the underlying estimates of soil erosion are too uncertain to justify more rigorous analysis. An exact measurement of the cost of soil erosion to the Malian economy would require more reliable measures of land degradation, an expanded data base on climate and land use, and improved models relating land degradation to economic production. On the other hand, even this simple analysis can show the rough magnitude of the economic costs incurred by land degradation, and their geographic distribution. It can provide a basis for discussion of the level and the locus of attention that should be paid to soil conservation in Mali.

II. NATURAL RESOURCE ACCOUNTING FOR MALI

A. The Context

Environmental decline has wide ranging impacts on economic welfare, through direct effects on primary production, as well as secondary effects on human health, relative prices, and demographic trends. How do we decide where to begin to quantify the economic effects of environmental decline in Mali? Some helpful questions might include: What are the major economic activities? What role do natural resources play in production? What is the relation between a particular activity and environmental deterioration? What are the technical options for, and costs and benefits of, remedial action?

Recent statistics published by the International Monetary Fund (1988) attribute roughly half of Mali's gross domestic product (GDP) to the primary sector, i.e., food crops, industrial crops, livestock, fishing and forestry. The country's major exports are cotton and livestock, which together account for about 70% of export revenues (1983-87). Mali's economic welfare clearly depends upon the fertility of her soil and the productivity of her vegetation.

A measure of the state of renewable resources in Mali might combine information on rainfall, soil fertility, and vegetable biomass. We would also consider the quality of man's management of natural resources. If the links between natural productivity and economic activity were known, we could estimate the effects of deterioration in any component of natural capacity over a range of productive activities. Much progress has been made in describing the interaction of natural and human production systems, but the picture is still patchy and imprecise. Data are scarce; models are imperfect.

It is nonetheless clear that natural phenomena and demographic pressure have recently put great strain on the fragile ecosystem of Sahelian countries. Both rainfall and good husbandry have been in short supply. Tree and grass cover have diminished, with disastrous consequences for the soil, which is left bare to the erosive winds and rains of the tropics. Production of crops and animals has surely suffered, but by how much? How important are these effects relative to technical advances and other adaptations? What impact have they had on Mali's economy? What options exist for remedial action?

B. Why Soil Erosion?

We do not propose to identify the links between all kinds of environmental decline and all sectors of Mali's economy. Such an undertaking is still quite unrealistic. We examine just one component of declining natural capacity - soil erosion - and explore its links to two economic sectors: traditional subsistence farming and "modern" agriculture. Among the food crops, we consider only those covering the largest surface areas, i.e. millet, millet with cowpea, sorghum, and maize. Rice is excluded from this analysis, on the assumption that virtually all of it is grown on low-lying flooded lands, which do not suffer significant soil losses. Among the modern or cash crops, we look at the impact of erosion on cotton and groundnut.

Why soil erosion and not soil fertility or rainfall? Why agriculture and not livestock production? The choice is primarily a function of the availability of useful models and reliable data, the vulnerability of the resource to depletion by man, and the potential for conservation.[1]

Ideally, we would consider soil fertility as a whole, measured in terms of soil chemistry, biology, structure, and productivity. We would estimate a trend for different soil classes and crops, with soil erosion by water only one variable in overall

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[1] A promising topic for future research would be the economics of rangeland depletion. Analysis of the productivity of Sahelian rangelands suggests that sustainability cannot be maintained at any useful level of production (Penning de Vries & Djiteye 1982). While traditional, extensive production will prolong the life of pasture, virtually every level of use will eventually deplete the resource. This argument, if true, implies that Mali should consider its pastures a non-renewable resource. The question then becomes one of deciding how quickly to run down the asset.

deterioration. The models needed for such analysis, however, are complex. Worse, much of the data required simply do not exist. Rates of soil erosion by rainfall, on the other hand, have been measured for various soils, crops, and climates throughout West Africa, often over many years. We thus use soil loss (in metric tons per hectare per year) as a proxy for declining soil fertility.

The precedent for this simplification comes from the IITA research station at Ibadan, Nigeria, along with much of our data and models. Through multiple regression analysis of controlled experiments, it was found that soil loss in tons per hectare was a reliable predictor of changes in soil nutrient content, soil pH, and moisture retention (Lal 1981). Moreover, the latter variables accounted for almost all of the annual variation in yields of maize and cowpea.

Despite its obvious importance to production, we do not consider the effects on agriculture of reduced rainfall, except insofar as it effects the rate of soil erosion. This is because no one farmer can affect rainfall. The farmer can and does affect the fertility of his land, however, by his choice of crops and rotation schemes, tillage practices, and other inputs.

This paper also ignores the effect on agriculture of deforestation, or more precisely, of a declining vegetable biomass. This is because the relation between the density of surrounding vegetation and agricultural productivity is both less direct and less well studied than the link between soil and crop production. The only information relevant to Mali comes from cost-benefit analyses of wind-break plantations in the arid and semi-arid zones of West Africa. Such an approach would entail yet another step away from things we can price directly. It would require estimating the effects of deforestation and loss of ground cover on soil temperature and moisture, and thence to crop yields.

C. Defining a Model

Soil erosion has been the focus of considerable study in West Africa, although not in Mali. Far less attention has been paid to quantifying the effects of soil loss on farm income. In another country, we might simply examine the market in agricultural land. A price differential between two plots which differed only in the extent of soil depletion would presumably capture the value of the lost soil. In Mali, however, there is essentially no legal market in agricultural land, and data from the illicit market are difficult to collect.

We are therefore forced to value the soil indirectly. Our approach is to examine the link between erosion and crop productivity. If we can determine the impact of soil loss on yields, we can infer its economic cost. The calculations can be summarized as follows:

1) estimate the mean rate of soil loss within each map unit (tons/ha/yr), as a function of rainfall, soil type and topography, crop cover and cultivation practices;

2) estimate the current annual crop yield foregone, a percentage of the mean yield on eroded land, as a function of the rate of soil loss;

3) estimate the net farm income foregone (CFA/ha/yr) resulting from every yield penalty, for the various crops grown;

4) estimate the surface area covered by each crop, and calculate the mean farm income foregone, for each map unit;

5) sum over groups of map units, for regional losses;

6) extrapolate from regional sums over Mali's total arable surface area, for national losses.

The calculations described are tenuous, and constitute only a first step in the analysis of soil erosion losses. Even if we can derive a reasonable estimate of the value of foregone crop yields, net of increased production costs, further research is required to determine what part of that loss reflects an optimal "extraction rate" for soil, and what part should be considered excessive. It is also by no means clear how to reflect excessive soil loss in aggregate measures of economic performance (the national accounts). These questions are presented in more detail in Appendix C, along with a description of different theoretical approaches to natural resource accounting. For this study, we simply assume that a significant part of the losses incurred are probably excessive, due to the insecurity of rural land tenure in Mali, and the inefficiency of rural capital markets. The latter assumptions are discussed in detail in Appendix G.

III. ESTIMATING SOIL EROSION

We employ the Universal Soil Loss Equation (USLE), despite serious reservations about its reliability in this application. The reason for using the USLE is that most of the climatic and soil data collected in West Africa during the past three decades were intended for its use. More specifically, the data available on land resources in Mali are readily converted into a form usable by the USLE model, while the data requirements of more sophisticated soil loss prediction models cannot be met with current information.

The Modified Universal Soil Loss Equation (Williams 1975), for example, is designed to estimate soil loss on a regional scale, but requires estimates of runoff volume and peak flow rates, neither of which can be readily derived from available data. Data are also too thin to permit use of two soil loss estimation models which, although less widely tested, were developed for the same agro-climatic zone as Mali (southern Niger), by Heusch (1980) and Vuillaume (1982). The former requires measurements of suspended sediment load at regular intervals along a watershed. The few gauging stations situated along the Niger River would permit only very gross estimates of soil loss, and would neglect a great deal of erosion and re-deposition in small upland catchments.

Vuillaume's models are even more demanding of data. The following parameters are all unavailable for Mali: the depth of surface runoff, precipitation during the first 20 minutes of each storm event, and the time separating the start of each storm from its maximum intensity.

Another model considered for this study is the Soil Loss Estimation Model for Southern Africa (SLEMSA), developed by Elwell and Stocking (1982). SLEMSA requires only three input parameters: the rainfall energy interception of each crop, the mean soil loss on a bare fallow plot of known slope, and a topographic factor for other slopes. The first parameter has been measured for crops in Zimbabwe, and may be applicable to Mali. The topographic input required by SLEMSA might be inferred from existing data on Mali, as we have done for use with the USLE. The difficulty lies with the second variable, which combines climatic erosivity and inherent soil erodibility. SLEMSA thus requires empirical data for rates of erosion on bare soil, over a representative range of environmental conditions. The few published measurements of soil erosion on bare fallow plots from countries neighboring Mali are not sufficient.

We thus resort to the Universal Soil Loss Equation (USLE), for which data are available. The USLE is nevertheless a compromise solution, for at least two reasons: (1) the USLE is designed for the study of small field plots, not for regional surveys, and (2) its validity in the tropics, despite three decades of study, is still a matter of controversy. The former is a more critical issue for the present study, since the USLE ignores soil deposition. When we consider that as little as 10% of the sediments eroded in any period reach a major river (Walling 1984, Crosson 1983), it becomes clear that soil deposition will have a significant mitigating effect, at least where such deposits occur. We attempt to allow for soil deposition in catchments, by discounting predicted soil loss on all lands known to receive significant alluvial deposits (Appendix E). As for the applicability of the

USLE in the tropics, we accept the conclusions of Roose (1977), who found the equation a reliable predictor of soil loss for the majority of cultivated lands in West Africa, especially for the gentle slopes and iron-rich soils typical of Mali.

The most important caveat on use of the USLE in Mali, or any soil loss estimation system, for that matter, stems from the lack of published data on soil erosion in that nation. It is thus impossible to verify estimates of soil loss except, very roughly, by reference to field measurements carried out in neighboring countries. As we show below, our synthetic estimates of soil erosion fall within the range of such measurements.

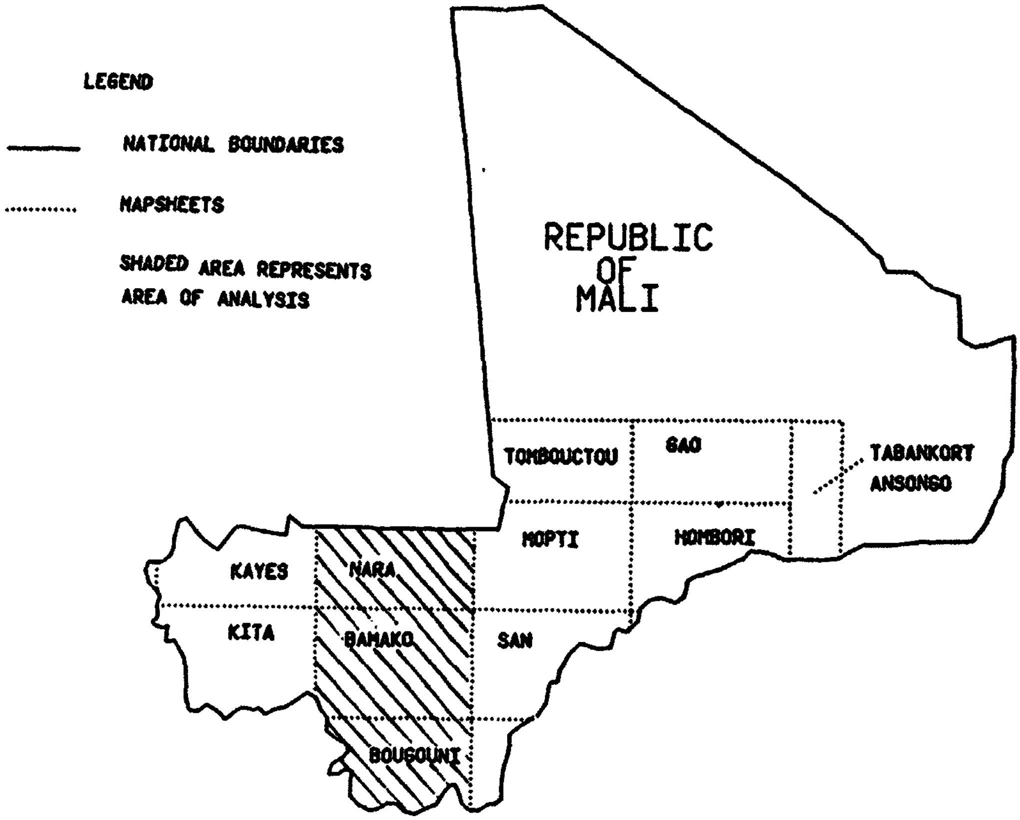
The calculations demanded by the Universal Soil Loss Equation are simple, once the values of its variables have been established. Average annual soil loss (A), in tons per hectare, is estimated as a function of six variables: the erosivity of rainfall (R), the inherent susceptibility of the soil to erosion by water (K), a slope length and steepness factor (SL), crop cover and soil management (C), and a correction factor for 'supplemental' conservation practices (P). The equation is multiplicative, whereby $A = R * K * SL * C * P$. In the following pages we describe how we have established, for each of the five variables, a range of values approximating the variation in climate, soil, topography, and land use within the study area.

A. Physical Data

Comprehensive information on soil resources, vegetation, rainfall and land use in Mali is contained in an atlas prepared from satellite (LANDSAT) images (Tippetts et al. 1983). Comprising a set of 33 maps, at a scale of 1:500,000, and extensive supporting documentation, the atlas also identifies land capability, the potential for water resources development, and other information not used here. The atlas is described in detail in Appendix D.

The TAMS atlas contains three sets of maps on soil and vegetation, rainfall and groundwater, and land use. The area covered by the maps (582,778 km^2) accounts for 47% of Mali's total surface area, and all of the country's arable land. That part of Mali receiving less than 200 mm mean annual precipitation is not covered. For this study we have analyzed three sets of map sheets (NARA, BAMAKO, & BOUGOUNI), covering 32% of the total TAMS study area. The three maps run north to south, providing a representative slice of the major agro-climatic zones of Mali (figure 1).

Figure 1.



B. Rainfall Erosivity

There have been few attempts to define the erosivity of rainfall in West Africa, most confined to specific areas, as part of studies of runoff and soil erosion. In every case, erosivity has been found to vary widely from one year to another, following swings in the level of annual precipitation.

On a broader scale, Delwaulle (1973) proposes a bivariate linear equation to predict rainfall erosivity (R) throughout the Sahel, based on an econometrically derived relation. His equation, however, requires data on the maximum intensity of rainfall, which few meteorological stations have collected. Roose (1977) argues that the ratio between climatic erosivity and the depth of annual precipitation is always about 0.50 in West Africa, except for seaside and mountain regions. He draws on rainfall levels recorded over 20 to 50 years at widely spaced stations, deriving a multiplier of 0.45 for the Ivory Coast savanna, with two rainy seasons, and 0.55 for the Sudanian and Sahelian steppe, with one rainy season.

If we compare Roose and Delwaulle's estimates of rainfall erosivity (R), we find a rough correspondence (within 10%). Roose's estimates are generally higher than Delwaulle's, perhaps because the latter uses records from a period of low rainfall, relative to long-term levels.

For this study we adopt Roose's approach, simply multiplying by 0.55 the value of the precipitation isohyets estimated by TAMS, and mapped in their atlas. This results in a very rough division of the study area into fourteen classes of climatic erosivity (R), which we plug into the USLE model. The values used here vary between 250, in the far North, to 800 near the Guinea border. Given the rough equivalence of the other USLE variables, throughout the study area, we found that most of the variation in predicted soil loss resulted from the difference in climatic erosivity.

C. Soil Erodibility

The information on soil erodibility contained in the TAMS atlas must be adapted to use with the USLE model, with some compromises. Firstly, the TAMS atlas provides only a qualitative indicator of soil erodibility for each of its 68 land classes. Secondly, their relative ranking incorporates both inherent soil erodibility and average slopes. Any assignment of numerical values to this ranking is therefore somewhat arbitrary, and may not reflect the true relative erodibility of different soil types. Nevertheless, for lack of better information, we adopt the qualitative rankings contained in TAMS atlas as a relative index of inherent soil erodibility (K), independent of slope. We have selected values of the soil erodibility factor based on published studies from West Africa (Table 1).

Table 1: Soil erodibility factor (K)

K value	Location	Source
0.004 - 0.137	Humid & sub-humid tropics	Lal 83
0.23 - 0.27	Burkina Faso (B.F.)	Fauck 78
0.04 - 0.17	Sefa, Senegal	Charreau 74
0.05 - 0.32	Gampela, B.F.	CTFT 79
0.06 - 0.20	Saria, B.F.	CTFT 79
	Ferruginous tropical soils from granite (B.F. and Ivory Coast)	Roose in Boodt & Gabriels (eds.) 80
0.01 - 0.03	- gravelly soils (self mulching)	
0.03 - 0.15	- after clearing old fallow	
0.20 - 0.30	- after 3-4 years cultivation	

For this study, we assign a numeric value to each of the three categories of soil erodibility defined by TAMS. For soils of "low" erodibility, we assign a value of 0.05; for "medium" erodibility: 0.15; and for "high" erodibility: 0.25. Where individual map units include soils of varying erodibility, the value of (K) for the unit as a whole is calculated as a weighted average of the different (K) values assigned to each of the soil types on which cultivation typically occurs. The weights on each soil type reflect not only the prevalence of that type in the map unit, but also the frequency with which each soil type is used for cultivation. Thus land which is grazed, as well as cultivated, or land only occasionally cultivated, is weighted less than land used only for agriculture. The weights are 25% for "occasional" cultivation, 50% for cultivation with "long fallow," 75% for land used for both farming and as pasture, and 100% for land used only for cultivation.

We also weight the (K) value by the density of clearing and cultivation in each map unit, based on findings by Roose (1980) and Lal (1983) that soil erodibility increases after land clearing, due to a decrease in organic matter content and a decline in the structural stability of the soil. TAMS identifies four categories of land use density, which refer to the percentage of cleared or cultivated land within a map unit. Where that proportion is between 30 and 60 percent, we multiply the (K) value by 1.5; where density is above 60% cleared or cultivated, we multiply the (K) value by 2.0. The resulting values of soil erodibility used in the model range between zero and 0.301, with a mean value on cropland of 0.064.[2]

D. Slope Length

The slope length factor (SL) was calculated in much the same way as the soil erodibility factor. Only slopes on cultivated soil units were taken into consideration, and these values were weighted both by the relative importance of the soil type in each map unit, and by the relative frequency of cultivation. We selected the minimum gradient (%) from the range given for each soil type, and used a short standard slope length (22.12 meters). The latter is a benchmark value, taken from a manual of soil conservation for West Africa (Centre Technique Forestier Tropical 1979). Because of the way the slope length factor is calculated, use of such a short slope length will tend to bias the USLE estimates downward (Table 2).

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[2] The average erodibility of all soil types identified in the atlas, independent of whether they are cultivated, is somewhat higher. The latter value is 0.10, which is fairly constant across the study area. In other words, cultivation appears to occur mostly on soils of low inherent erodibility, relative to the overall mean.

We found that slopes on regularly cultivated land in the study area rarely exceeded 6%. The weighted average slope, in the area studied, is only 3%. The corresponding slope length values range from zero to 0.76, with a mean of 0.28.

Table 2: Slope length factor (SL)

slope length (m)	Slope in percent									
	2	4	6	8	10	12	14	16	18	20
20	.18	.35	.57	.84	1.2	1.5	2.0	2.4	3.0	3.6
30	.25	.50	.70	1.0	1.4	1.8	2.4	2.9	3.5	4.3
60	.35	.65	1.0	1.5	2.0	2.6	3.3	4.2	5.0	6.0
90	.40	.75	1.2	1.8	2.5	3.3	4.1	5.1	6.2	7.5
120	.45	.90	1.4	2.0	2.8	3.8	4.7	5.9	7.2	8.8

E. Crop Cover and Soil Management

TAMS identifies three major crops in each land use map unit. This data may be converted into numerical estimates of crop cover factors (C). The conversion is based on field studies in West Africa, for which values are presented in Table 3. For comparison, the table includes representative crop cover values (C) for other types of ground cover, such as rice, fallow, and forest. As can be seen, soil under field crops is significantly more susceptible to erosion by rainfall than is land under almost any other cover.

Table 3: Crop cover and management factor (C)

	Fauck (78)	Techniques Rurales en Afrique (69)	Greenland & Lal (77)	Singh et al. (85)
Trad. millet or sorghum	0.4 - 0.9	0.6 - 0.8	0.3 - 0.9	
Cotton	0.5 - 0.7		0.5	
Peanuts	0.4 - 0.8		0.4 - 0.8	
Cowpea				0.28
Maize				0.42
Rice (paddy)				0.28
Fallow		0.3		
Prairie in good condition	0.01		0.01	
Prairie burned or over-grazed	0.1			
Dense forest			0.001	
Bare plot		1.0		

Based on these figures, we assign the following values to each of the major crops grown in the study area: for millet, sorghum, peanuts, and cotton, C = 0.6. For maize, C = 0.42, and for cowpea C = 0.28. These are average values. The crop cover factor actually varies during the growing season, mirroring the degree to which plant foliage protects the soil underneath.

Since more than one crop is grown in most map units, the (C) value is calculated as the weighted average of the values of each of the three major crops found in the unit. We use arbitrary weights of 50% for the first crop, 30% for the second, and 20% for the third. In fact, the relative distribution of primary and secondary crops varies from the most arid to the more humid zones (see below). This has little consequence, however, in the calculation of (C) values. Since the first and second crop in almost all map units where cultivation occurs, and where there is no significant soil deposition, is either millet or sorghum, (C) values are all very close to 0.6.

F. Conservation Practices

The USLE also corrects for the use of conservation practices (P), such as contour plowing, mulching, or terracing. The benchmark value (1.0) refers to conventional plowing expecuted perpendicular to the slope of the field. (P) may go as low as 0.01, with a thick straw mulch. It is difficult to assign values of (P) for Mali, since we have little data on how soil management and tillage techniques vary across the country. For the present study we adopt a value of P = 0.8 in the "Sudanian" and "Northern Guinean" zones (where rainfall is above 600 mm), and P = 0.6 in the "Sahel." The distinction is based on the fact that farmers in less humid regions do not till their mostly sandy fields, but sow directly into small pockets. As they do not disturb the surface crust, there is subsequently less soil loss. Farmers in more humid zones, on the other hand, are obliged to turn the soil completely, to reduce weeds. The majority of the farmers in the study area still till by hand, leaving no channels for runoff. A growing minority use plows, typically with little attempt to follow contours.

Sample values of (P) are presented in Table 4, using data from Burkina Faso, Ivory Coast, Senegal, and Niger. Note that these figures permit us to estimate the potential benefits of various conservation techniques, in terms of soil erosion avoided.

Table 4: Supplemental (conservation) practices

	in Roose (77)	Techniques Rurales en Afrique (69)
contour trench (tied ridges)	0.1 - 0.2	
strip cropping	0.1 - 0.3	0.3 - 0.45
straw mulch	0.01	
dry stone ridges	0.1	
grass fallow	0.1 - 0.5	
contour plowing		0.6 - 0.9
terraces		0.3 - 0.9

G. Estimates of Erosion

Empirical measurements of soil erosion are not available for Mali. Hence we cannot directly verify soil losses estimated with the USLE. Instead we use field data from studies in neighboring West African countries, for comparative purposes. There have been numerous, multi-year measurements of soil erosion under various management techniques, mostly for comparing the benefits of soil conservation to traditional techniques of cultivation. Of immediate concern to us are rates of erosion under conventional cultivation.

The data are quite variable. Some representative values of soil loss at stations in neighboring countries are presented in Table 5. These are useful reference points, for comparison with rates of erosion estimated by the USLE from TAMS data, for similar soils, topography, rainfall levels and land uses.

Our estimates of erosion on Malian farms are presented in maps included in Appendix A.1. Estimated soil loss on cultivated land averages only 1 ton per hectare per year, in the North, but over 10 tons/ha/yr, on average, in the far South. For the study area as a whole, the average estimated soil loss is 6.5 tons/ha/yr, which matches the mean rate of erosion measured under comparable conditions, in neighboring countries.

The highest rates of estimated erosion (31 tons/ha/yr) are in the southern "Sudanian" zone, and result from both relatively high rainfall, and somewhat higher values for soil erodibility (K). The latter may be attributed to the greater density of cultivation in the area, which in turn probably reflects relatively high population densities. Although our maximum estimated annual soil loss exceeds the highest rate cited in Table 5, it is still low compared to erosion measurements at some stations in the Ivory Coast, which have recorded losses over 500 tons/ha/yr (Roose 1986).

Table 5: Soil loss under traditional cultivation in West Africa

Country	Station	Source	Mean Rainfall (mm)	Slope (%)	Mean Erosion (t/ha/yr)	
					Crop	Fallow
Nigeria	Ibadan	R. Lal (76)	1282	1	.70	
		"	1282	5	3.50	
		"	1282	10	3.40	
		"	1282	15	13.80	
Senegal	Sefa	CTFT (79)	1200	1.5	7.45	4.9
Ghana	Nyankpala	Bonsu (81)	1082	2	.20	
Burkina	Ouagadougou	Charreau (72)	850	.5	4.30	.08
	Gampela	Roose (84)	731	.8	4.06	
	Gonsé	"	691	.5		.15
	Saria	"	643	.7	6.0	.50
	"	"	850	1.7	7.3	.17
	Linoghin	"	636	1.3		.80
	Sirgui	Koutaba (86)	692	.08	7.3	5.7
C. Ivoire	Divo	Roose (86)	1550	10		.43
	Bouake	"	1200	4	13	.05
	Korhogo	"	1350	3	4	.11
Niger	Kountkouzout	Vuillaume (82)	450	1	1.4	
	"	"	450	3	12.7	6.4
	"	"	450	12	17.0	9.9
	Allokoto	Delwaulle (73)	440	3	9.5	
MEAN:			920 mm	4%	6.8 t	2.4 t
STD. DEVIATION:			362 mm	4%	4.9 t	3.4 t
MAXIMUM:			1550 mm	15%	17.0 t	9.9 t

IV. THE EFFECTS OF SOIL EROSION ON CROP PRODUCTIVITY

We value soil loss by translating tons of erosion per hectare per year into foregone farm income that would have been earned if the soil had stayed put. Studies carried out both in Africa and the United States suggest that this is a tricky step. Crop yields are a function of many variables, of which soil fertility is only one. Furthermore, as noted above, mean annual rates of soil loss can only be considered a rough proxy for declining soil fertility. They may also be offset by organic or chemical fertilization, or other soil management techniques.

Nevertheless, in side-by-side experiments which attempt to control for other variables, it appears that loss of top soil has a measurable and generally negative effect on crop yields. One of the most rigorous predictive models is the EPIC model (Erosion Productivity Impact Calculator), developed by the US Soil Conservation Service (Williams et al., 1982). The EPIC model has not been adapted for the tropics, however, nor do we have the physical data required to apply it. Moreover, yields in the tropics appear to be more sensitive to soil loss than in temperate climates, given the low fertility, shallow depth, and fragile structure of many tropical soils (Lal 1987b).

A. The Erosion-Yield Relation in Africa

We found only one model of the erosion-yield relation in West Africa, based on research carried out by the International Institute for Tropical Agriculture (IITA) in Ibadan, Nigeria (Lal, 1981). The effect of cumulative soil loss on crops under continuous cultivation was estimated econometrically, by comparison of maize and cowpea yields on side-by-side plots under varying levels of natural soil erosion. Use of the model under Malian conditions is questionable, but certainly more appropriate than anything available from temperate zones, given our data constraints.

Both southern Mali and south-western Nigeria share, among other things, soils of poor inherent fertility, weak structure, and low erodibility (Lal 1987a). The two countries are also both characterized by an extremely erosive climatic regime, with intense, highly variable rainfall. We thus assume that crop yields in Mali are no <u>less</u> sensitive to soil loss than they are in Nigeria, although actual rates of erosion may vary. The model itself consists of a simple exponential relation, as follows:

$$Y = C^{-\beta x}$$

where: Y = yield in tons per hectare
C = yield on uneroded (newly cleared) land
β = coefficient varying with crop and slope
x = cumulative soil loss in tons per hectare

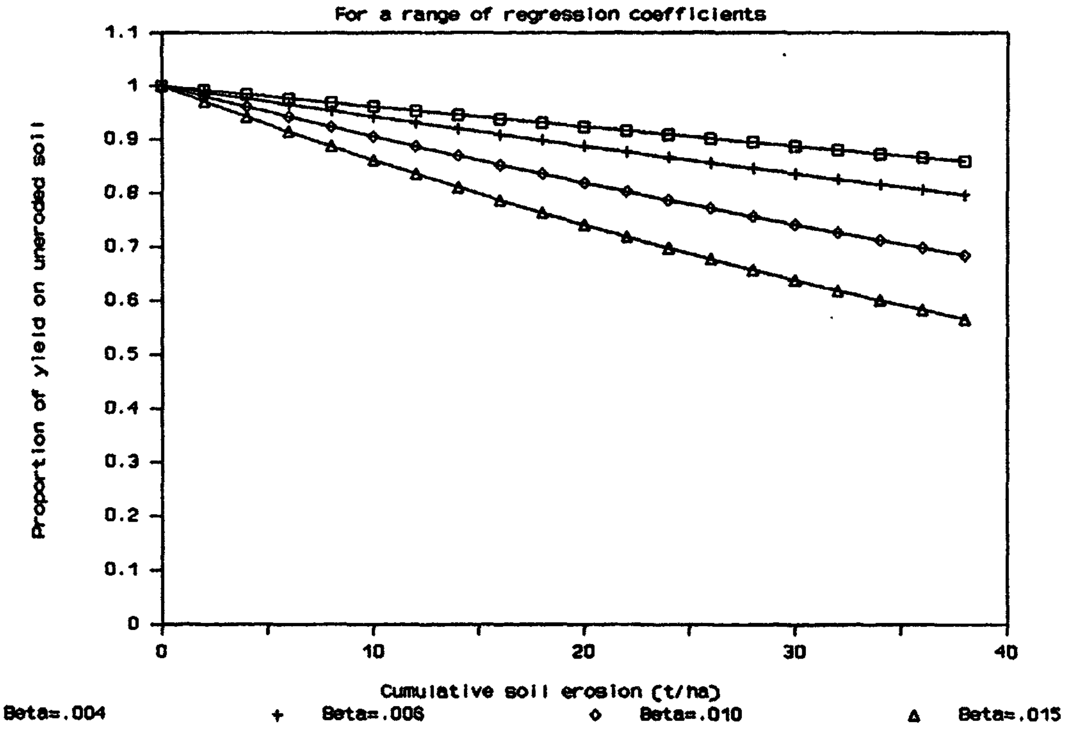
Note that the functional form implies that annual yield losses will gradually decrease with cumulative erosion. This conforms to our intuition that crops will be relatively intolerant of initial soil losses, due to the shallow fertile horizon of the soils studied. Lal estimated eight equations, one for each crop and four slopes (1, 5, 10, and 15%). The estimated coefficients (β) varied between 0.002 and 0.036 for cowpea, and between 0.003 and 0.017 for maize, with the greatest losses recorded, curiously, on the most gentle slopes (1%). All but one of the Beta coefficients relating yield to soil loss are significant to at least 5%.

The correlation coefficients (r), measuring the degree to which yield varied with soil loss, were generally higher for maize (0.86 to 0.99) than for cowpea (0.66 to 0.97), with the closest relation observed at gentler slopes. As noted above, multiple regression analysis relating soil loss and yields to a number of other constituents of soil fertility established that soil loss was a reliable predictor of fertility decline, and thus of yield losses.

For this study, we apply Lal's regression equation uniformly, to all crops and in all regions. In fact, crops yields are probably not uniformly sensitive to soil loss across all of Mali. We would expect sensitivity to vary by crop, soil type, rainfall, and other factors. Our data base, however, is too thin for such distinctions. In practice, we also drop the constant (C) and calculate a percentage change in yield, for every level of soil erosion.

Figure 2.

EFFECT OF SOIL EROSION ON CROP YIELDS



The crop budgets used here to value yield changes are derived from land continuously cultivated, and thus subject to erosion, for an average of ten years (Matlon & Fafchamps, 1988). Hence we multiply estimated annual soil loss (x) by ten, for the mean level of cumulative erosion. We then apply Lal's equation to calculate the total decline in yield, for ten years of cumulative soil loss. We also calculate the total decline over nine years. Taking the difference between the two values, we can estimate the percent of the yield in year ten that is foregone due to erosion in year nine, i.e., current foregone yield. By varying the exponential coefficient (β), we derive a range of yield penalties, which may include the true impact of soil loss. We use four coefficients: $\beta = 0.002$, 0.006, 0.010, and 0.015, all of which lie within the range of values estimated by Lal. Figure 2 shows the percentage change in yield incurred for each of these coefficients, for various levels of cumulative soil loss.

One way to check the yield penalties estimated with Lal's equation is by comparison with measured yield trends under continuous cultivation. Experiments carried out in Kano, Nigeria, from 1931 to 1955, provide average annual yields for groundnut, millet and sorghum, with and without manure, under continuous cultivation from clearing (Nye & Greenland, 1960). We assume that over 24 years of measurement, annual climatic variation cancels out, so these figures are taken to reflect both soil erosion and exhaustion of soil nutrients (Table 6).

Table 6. Declining yields under continuous cultivation

(from Nye & Greenland, 1960)

	Groundnut		Millet		Sorghum		mean percent change per year	
Year	w/o	w/	w/o	w/	w/o	w/	w/o	w/
1931 - 35	1015	1283	922	1164	543	1141		
36 - 40	784	1126	455	836	328	1014	- 9.2	- 3.8
41 - 45	698	1015	318	658	105	942	- 9.9	- 2.8
46 - 50	323	634	546	1053	91	935	- 2.3	+ 0.3
51 - 55	511	848	330	864	-	-	+ 0.4	- 0.9
Total Decline (%)	50	34	64	26	83	12		

All yield figures in metric tons per hectare.
(w/o) designates plots without manure; (w/) designates plots receiving 6.7 t/ha manure each year.

It might seem curious if annual changes in yield estimated using Lal's regression equation were much greater than the highest annual rate of yield decline measured at Kano, for all crops (i.e., 9.9%). In practice, mean estimated yield penalties only exceed 9.9% when Beta is assigned a value of 0.01 or higher, and then only for lands in the far South. The average yield penalty for the BOUGOUNI map sheet, for example, is about 16.5% when Beta = 0.015.

One may argue, on the other hand, that today's soil is less capable of sustaining yields, after decades of increasingly intense exploitation. This interpretation is supported by more recent studies of continuous cropping in West Africa, one of which shows maize yields dropping an average of 43% per year, over four years (Sobulo & Osiname 1986).

B. From Crop Yields to Farm Budgets

The relation between crop yields and farm income is clearly not strictly proportional. A decline in yield, for example, may result in a more than proportionate fall in farm income, due to the inflexibility of certain fixed costs. Likewise, an increase in yield will entail some additional effort for weeding, harvesting, and storage, but because many input costs are fixed, the percentage increase in farm income may exceed the percentage yield increase.

To model these effects, we use farm budgets published by the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), based on research in Burkina Faso (Matlon & Fafchamps, 1988). Soils, climate, production systems, and prices are all comparable to Mali. These budgets are preferred to those prepared for Mali by TAMS for two reasons: (1) TAMS relies on more questionable production data (collected by the para-statal Opérations de Développement Rurale), and (2) the atlas documentation only includes a small selection of budgets -- most are housed in Bamako, Mali. In any case, when we performed a preliminary calculation of how a fixed change in yields would affect farm income, both the TAMS budgets and the ICRISAT budgets showed similar results.

The crop budgets published by ICRISAT include 21 crop combinations in 3 climatic zones (Sahelian, Sudanian, and Northern Guinean). We use here only seven crop combinations, corresponding to the seven major crops identified in TAMS land use maps. We also condense the budgets, distinguishing only five components: crop value, fixed capital inputs, fixed labor, variable labor, and returns to land (CFA/ha). The budgets are listed as used in Appendix F.

The mechanics of converting an estimated percentage change in yield into a monetary change in farm income is straightforward. For each of the three major crops found in every map unit, we calculate the impact of a percentage increase in yield (i.e. yield foregone due to erosion) as follows:

1) apply the percentage yield foregone, estimated from the regression equation, to the gross value of the harvest;

2) increase by the same proportion that part of the labor input that is a function of yield (weeding and harvesting);

3) maintain fixed costs unchanged, and recalculate the net returns to land (CFA/ha);

4) subtract the new net return (without erosion) from the original net return (with erosion), to derive net return forgone (CFA/ha);

5) weight returns foregone by the relative importance of each crop in the map unit.

The weights used to adjust for crop importance are not constant across the study area. According to Matlon and Fafchamps (1988), the relative proportion of the total cultivated surface area occupied by each crop varies according to the agro-climatic zone (Table 7). Crop mixes are more diversified in the South, a fact the authors attribute to the greater flexibility offered by more generous climate and soils. Accordingly, we weight the foregone income calculated for the first, second and third crops as follows: N. Guinea zone: 40, 30, and 30%, respectively; Sudanian zone: 60,30, and 10%; Sahelian zone: 90,5, and 5%.

Table 7. Percentage of cultivated land occupied by each crop

Agro-climatic Zone	Millet	Sorghum	Maize	Groundnut	Cotton	Other
N. Guinea	22	37	5	1	29	6
Sudan	27	60	2	8	1	2
Sahel	93	3	1	0	0	3

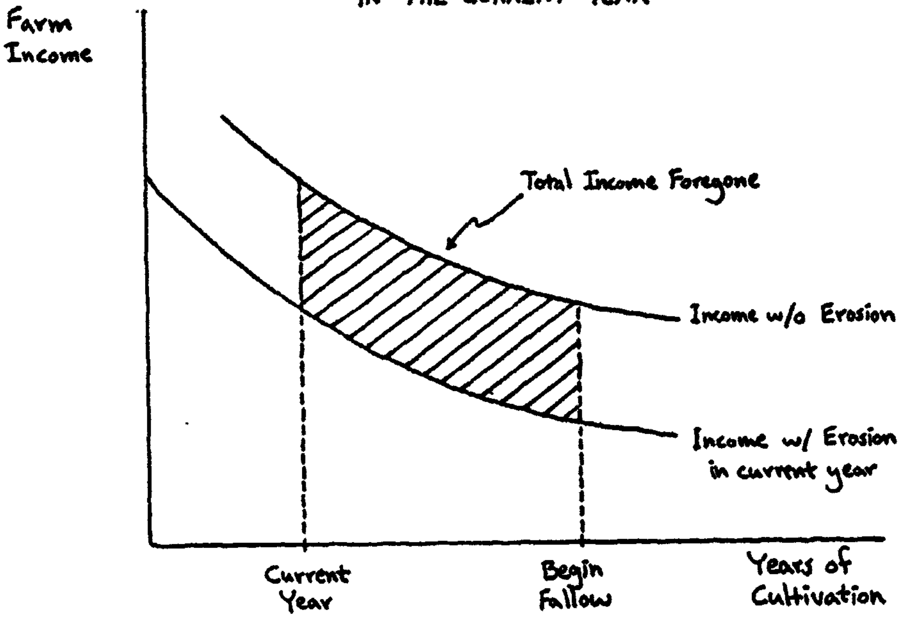
Recall that we exclude rice from our calculation of erosion impacts, on the assumption that rice is grown exclusively in natural depressions, or on alluvial plains, which may incur some soil loss but probably also receive significant sediment deposits. This exclusion only makes a significant difference to average losses per hectare in the BAMAKO map sheet, due to the relatively large proportion of land devoted to rice, along the Niger River.

The resulting foregone income per hectare, derived from the calculations described above, does not account for all of the economic loss incurred. Land degradation in any one year is presumed to affect yields in subsequent years, as well. We assume that the nominal value of current income foregone, due to just one year of soil loss, will also be lost in subsequent years, until the land is fallowed (figure 3).[3] We can calculate the present value of that foregone income stream, for various rates of discount and time horizons.

For the base case, we assume a conservative discount rate of 10 percent and a moderately long time horizon of 10 years until fallowing. We use 1985 prices, for comparison with other published data (see below). With these assumptions, for the study area as a whole, we find that the mean present value of income foregone over ten years, due to one year of soil loss, ranges between 2 and 8 thousand CFA/ha, for Beta = 0.004 and 0.015, respectively. To put these sums in perspective, note that average net farm revenues, over the entire study area, are about 9,700 CFA/ha/yr (excluding rice).

Figure 3.

FOREGONE FARM INCOME FROM EROSION IN THE CURRENT YEAR



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[3] This assumes complete restoration of soil fertility and crop yields through fallowing. Given the ever shorter duration of fallow periods, this assumption may be too generous. Fallowing may not fully compensate for damage done by erosion, in which case we underestimate the value of future losses. Yields are assumed to decline even without erosion, due to exhaustion of soil fertility by crops. We ignore the likelihood that, without erosion, the period of cultivation would be prolonged.

When we break down estimated revenue foregone by agro-climatic zone, we find differences which reflect not only varying levels of soil loss, but also the relative profitability of farming from North to South (Table 8). Average erosion losses are greatest on the BOUGOUNI map sheet, where even modest estimates of income foregone (Beta = 0.004) are equivalent to 54% of the region's average net returns to dry land farming (9,100 CFA/ha/yr).

Table 8. Present value of income foregone due to one year of erosion

(r = 10%, t = 10 yrs., 1985 CFA/ha)

Map sheet	Beta = 0.004	Beta = 0.006	Beta = 0.010	Beta = 0.015
BOUGOUNI				
Average	4,913	7,461	12,752	19,746
Maximum	13,550	20,751	36,063	57,047
BAMAKO				
Average	1,683	2,555	4,360	6,741
Maximum	20,050	31,049	55,211	89,960
NARA				
Average	242	364	611	922
Maximum	4,239	6,392	10,767	16,368

Regional averages, in turn, obscure very high levels of revenue foregone on some map units, especially in central and southern areas (BOUGOUNI and BAMAKO). The highest losses per hectare are found on the BAMAKO map sheet where, for the same assumptions of time preference and time horizon as above, maximum losses reach about 20,000 CFA/ha (Beta = 0.004), for every year of soil erosion. Average net returns to farming, on these same map units, do not exceed 12,000 CFA/ha/yr. These figures imply that net real returns from farming may be negative, on land subject to high rates of erosion, when the value of foregone future yields, due to soil loss, exceeds net farm income in the current year.

C. Erosion Losses and the Cost of Conservation

Another way to look at estimated erosion losses is to compare the value of income foregone to the cost of soil conservation measures. Data for the latter come from cost-benefit analyses of water harvesting technologies promoted in West Africa. The only technologies for which the costs of implementation are comparable to our estimated losses are simple water harvesting and erosion control measures, such as contour plowing, tied ridges, rock lines or contour bunds, and grass strips. More expensive measures, such as terracing, do not appear to be justified by the level of losses resulting from soil erosion. On the other hand, most soil conservation measures have the important secondary benefit of increasing rainfall infiltration. We do not attempt to quantify the magnitude of such additional benefits here, although clearly they will make any technology more attractive.

To illustrate the approach, we use data from three cost-benefit analyses of a simple water harvesting and erosion control technique, from Burkina Faso (CILSS 1988, Matlon 1985) and Mali (CILSS 1988). The studies evaluated the use of rock lines along contours (combined with grass strips in Mali), in terms of capital and maintenance cost, and the benefits of increased crop yields.[4]

Relative to yields on adjacent untreated plots, various authors cite increases from 9% to 90% due to the use of rock lines along contours in Burkina Faso (Table 9). These benefits are assumed to reflect not just the conservation of soil on-site, but also increased moisture availability due to reduced runoff, and possibly deposition of fertile sediments from land above the treated plots. It seems likely that the benefits of increased water availability will dominate other effects where rainfall is scarce. Where water is less of a limiting factor, the benefits of erosion control will become more important (Matlon 1985).

Table 9. Yield benefits of water harvesting measures

(relative to adjacent untreated plots)

Technique employed	Yield benefit (%)	Source
stone bunds (farmers)	12 - 90	Reij et al. 1988
rock bunds (farmers)	59	"
'diguettes en pierre'	40	Critchly & Reij 1987
rock ridges	35	CILSS 1988
rock bunds (station)	9 - 40	Matlon 1985

Estimates of the costs of soil conservation are of more immediate concern here. The three analyses cited report a single capital investment, in the first year, ranging from 21,500 to 30,000 Francs CFA/ha (1985 prices). All three also report indefinite annual maintenance costs ranging from 2.5% to 33% of the initial investment. They determine the present value of those costs, over fifteen and twenty year time horizons, using discount rates of 15% and 10%. We can easily normalize their figures, to a ten year time horizon and 10% discount rate, as in Table 10.

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[4] Water harvesting is virtually synonymous with soil conservation. Both aim to reduce runoff from rainfall, the primary cause of soil erosion.

Table 10. Present cost of conservation measures

(r = 10%, t = 10 yrs., 1985 Francs CFA/ha)

Technique & location	Present Cost	Source
horizontal rock ridges Burkina Faso	47,300	CILSS 1988
rock lines and grass strips, Mali	69,100	"
rock bunds: 30,000 CFA/ha with 10% maintenance, Burkina Faso	47,300	Matlon 1985
rock bunds: 21,525 CFA/ha with 7% maintenance, Burkina Faso	30,200	"

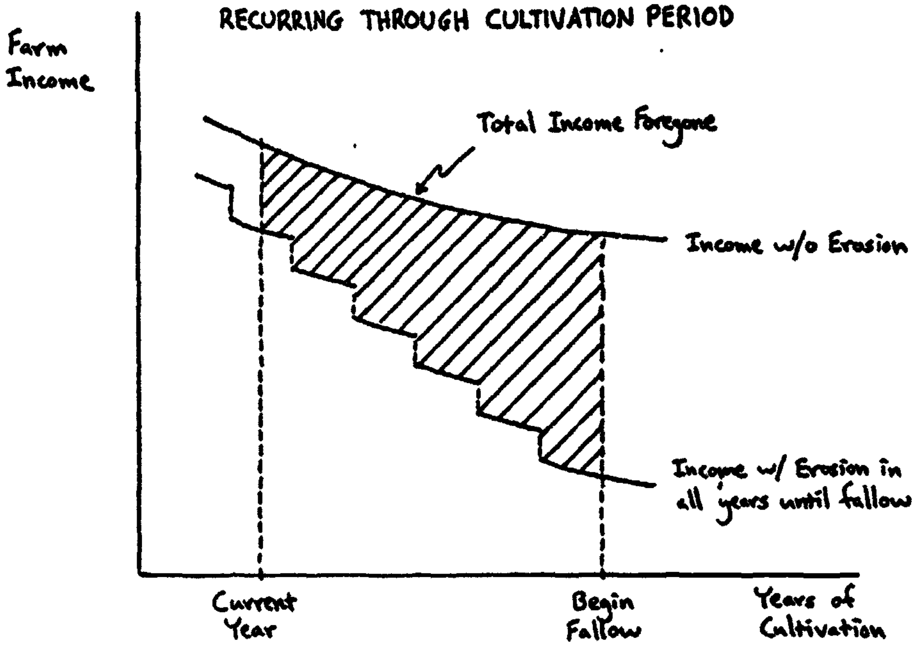
Note that these capital costs cover only the outlay by farmers, in the form of dry season labor. Excluded are funds spent by governments and foreign agencies, to teach and encourage farmers to adopt the technology. Some information on the latter comes from Wright (cited in Reij et al. 1988), who estimated average project costs per hectare treated, for a program in Burkina Faso. Even there, the salaries of government agents were excluded, as was the depreciation of the project's capital equipment.

The figures are nonetheless instructive. Wright estimated project costs at 771,400 CFA/ha in 1981, declining to 17,300 CFA/ha in 1985, and 8,510 CFA/ha in 1986 (assumed to be nominal amounts). Assuming that only one year of average project expenses would be charged to each hectare treated, and taking the lowest capital cost figure from Table 10, we might estimate the minimum average cost of the technology at about 40,000 CFA/ha (30.2 K + 8.5 K). If we assume slightly higher administrative and capital costs, we would expect a cost of 65,000 CFA/ha (47.3 K + 17.3 K). Finally, for the first years of a project, we project costs over 100,000 CFA/ha.

In comparing these costs of conservation to our estimates of foregone farm income, we must make one more adjustment. We have calculated above the present value of income foregone due to erosion in only one year. In comparing erosion losses to conservation costs, we must consider losses in every year of the time horizon, until fallowing. With a ten year horizon, for example, gross losses will include the present value of foregone future income attributable to erosion in the first year, plus the present value of all losses resulting from erosion in the second year, and so on until year ten (figure 4). As above, we ignore the likelihood that cultivation would be prolonged, without erosion, and thus underestimate the value of total losses.

Figure 4.

FOREGONE FARM INCOME FROM EROSION RECURRING THROUGH CULTIVATION PERIOD



We make this adjustment, using the assumed 10% discount rate and 10 year time horizon, in order to identify map units where the present value of foregone farm income, due to erosion, exceeds the estimated cost of installing and maintaining rock lines along the contours. These are shown on the maps in Appendix A, assuming the lowest cost of installing and maintaining rock lines, for a range of assumptions about the impact of erosion on crop yields (Beta). The maps identify areas where yield losses due to erosion may justify conservation efforts. By varying the magnitude of the impact of soil loss (Beta), we establish a priority ranking of areas which merit attention.[5]

The information is summarized in Table 11, where we also vary the presumed cost of conservation. The table presents the number of individual map units, and the total surface area cleared or cultivated, where gross erosion losses exceed the cost of conservation. For example, if we assume that the impact of erosion on crop yields is moderate (Beta = 0.006), and that it costs 65,000

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[5] Note that we implicitly assume that contour bunds are 100% effective in halting net soil loss. Relaxing this assumption would reduce the number of map units where foregone income exceeds the cost of conservation, without altering their distribution. Increasing the assumed cost of conservation has the same effect.

CFA, in present value terms, to install and maintain contour bunds over 10 years, then we can distinguish 48 map units, with a total cultivated surface area of 139,973 ha, where the present value of farm income foregone over the same period exceeds the cost of the bunds. Note that this method of selection depends critically on the choice of a discount rate. Since the largest cost component of soil conservation occurs in the first year, while the nominal cost of erosion is constant from year to year, a lower discount rate would increase the number of map units with losses exceeding the cost of conservation. We will discuss the effect of varying this and other assumptions in more detail below.

Table 11. Where erosion losses exceed the cost of conservation

(r = 10%, t = 10 yrs., 1985 Francs CFA/ha)

	Cost of soil conservation			
BOUGOUNI, BAMAKO, NARA	40,000	65,000	100,000	200,000
Beta = 0.004				
Number of map units	52	6	0	0
Area of crop/clear (ha)	206,929	19,634	0	0
Beta = 0.006				
Number of map units	158	48	6	0
Area of crop/clear (ha)	558,819	139,973	19,634	0
Beta = 0.010				
Number of map units	312	175	58	5
Area of crop/clear (ha)	906,587	629,682	219,581	6,006
Beta = 0.015				
Number of map units	402	309	172	36
Area of crop/clear (ha)	1,108,330	905,391	584,222	119,565

Not surprisingly, the greatest losses occur where we find a combination of relatively steep slopes, high rainfall, and dense cultivation. There are 36 map units, with a total of 119,565 hectares cleared or cultivated, where losses exceed 200,000 CFA/ha over ten years. These map units are all situated in what Matlon and Fafchamps call the Sudanian zone, where traditional farming is most profitable. The proportion of land cleared or cultivated on these map units is between 31 and 60%, higher than the average agricultural density over the entire study area (about 20%), but below the maximum density reported by TAMS (category 4: > 60%). The principal crops in these map units are sorghum and millet, typical for the region.

V. SOIL EROSION AND NATIONAL INCOME

The final component of our analysis is to evaluate the gross impact of soil erosion on the Malian economy as a whole. The results presented so far are based on analysis of just three out of eleven TAMS map sheets (BOUGOUNI, BAMAKO, NARA). To estimate gross losses on a national scale, we assume that these map sheets are representative of the rest of Mali. We also ignore the price effects of increased agricultural production nationwide, if erosion did not occur.

To aggregate the farm level losses estimated for each map unit, we first multiply losses per hectare by the total surface area of the map unit, and by the relative density of farming in each unit (assumed to be 50% of the area cleared or cultivated). We then sum over all map units, to derive the estimated gross economic loss. To account for the varying levels of losses occurring in different agro-climatic zones, we have aggregated the northern and southern halves of each map sheet separately.

Extrapolation to the national level simply involves extending gross losses, estimated for each of the six sub-map sheets, to comparable regions. This requires some idea of the surface area of the map sheets not analyzed. We have approximate figures, based on the TAMS atlas, which permit an estimate of the multipliers to be applied to gross losses in the study area. Some challenge is presented by the Inner Niger River delta, a vast floodplain which does not show up on the map sheets studied. We adjust by reducing the area to which we extrapolate estimated losses, on the assumption that little erosion occurs in the delta.

Table 12 presents foregone income losses resulting from an average year of soil erosion, under the most conservative assumptions of the impact of soil loss on crop yields (Beta = 0.004), and with the same assumed time horizon and time preference used above (ten years until fallowing, 10% discount rate).

One way to check the numbers in Table 12 is to use the crop budgets, and the TAMS atlas, to generate our own estimate of national agricultural income. We estimate a total cropped surface area of about three million ha (1979-80 data, Appendix F). Using the budgets for all crops, including rice, we derive a figure for gross national income from farming by summing up gross farm income in each map unit (the value of the harvest). The result - 154 billion CFA in 1983 prices - is within 2% of the figure cited by the International Monetary Fund, for traditional and modern agriculture in the same year (IMF 1988). Although such accuracy is probably coincidental, it suggests that our estimates of nationwide losses are of the right order of magnitude.

Table 12. Estimated annual nation-wide foregone farm income

(r = 10%, t = 10 yrs, β = 0.004, est. 1988 prices, US $1 = 300 CFA)

Map Sheet	One Year Map Sheet Loss (CFA millions)	Comparable Surface Area (Multiplier)	One Year National Loss (CFA millions)
BOUGOUNI (South)	242	1.25	303
BOUGOUNI (North)	154	1.25	192
BAMAKO (South)	159	2.83	451
BAMAKO (North)	91	3.48	318
NARA (South)	25	3.50	88
NARA (North)	6	4.35	25
			1,377

	US Dollars (Millions)	Francs CFA (Millions)	% Mali GDP*	% Agr. GDP**
Nationwide Annual Income Losses on Farm Land :	4.59	1,377	0.23	0.59
Discounted Present Value Foregone Farm Income :	31.00	9,301	1.54	3.95

* est. from 1987 data: GDP = 572 Billion CFA; inflated 5.5%
** includes only farming; estimated from 1984 data: contrib. to GDP from trad'l. & mod. agr. = 174 Billion CFA; inflated 35%

A. Sensitivity Analysis

All of the analysis presented above relies on assumptions that cannot easily be verified. Predicted soil losses are the most obvious instance, and the most fundamental. Verifying our synthetic estimates of soil erosion could require years of painstaking measurement in the field. Other components of the models developed above are also susceptible to criticism, but their influence is more readily checked.

Table 13 presents gross farm income losses as a percent of agricultural GDP, for a range of discount rates and time horizons, and for various assumptions about the severity of erosion's impact on crop yields (Beta). These assumptions appear to have the greatest effect on the magnitude of our estimates. If we insist on a short time horizon and a high discount rate, then future revenues foregone due to soil erosion appear small (2 to 9%), relative to current farm income. Taking a longer view, erosion losses seem far more significant. Additional factors that would affect our estimates include the length of slopes on farm land, the ratio of land under crops to fallow land, and the change in variable costs resulting from a change in yield. The latter parameters are not tested here.

Table 13. Sensitivity analysis: nation-wide foregone farm income

(% of estimated 1988 agricultural GDP*)

Years until Fallowing	Discount Rate	Beta			
		0.004	0.006	0.010	0.015
5	15%	2.26	3.42	5.81	8.94
	10%	2.44	3.70	6.28	9.67
	5%	2.66	4.03	6.85	10.54
10	15%	3.38	5.12	8.70	13.38
	10%	3.95	5.99	10.18	15.67
	5%	4.74	7.19	12.22	18.79
20	15%	4.21	6.38	10.85	16.69
	10%	5.48	8.30	14.11	21.71
	5%	7.66	11.60	19.72	30.33

* contribution to 1984 GDP from traditional. & modern agriculture = 174 Billion CFA; inflated by 35%

B. Conclusion

The major practical conclusion of this study is that economic losses due to soil erosion in Mali are probably high enough, in certain areas, to justify moderate investment in farm-level soil conservation, under even relatively conservative assumptions. These areas are identified by dark shading in the maps presented in Appendix A. Under more extreme assumptions about the impact of erosion on crop yields, and more favorable assumptions about the cost of soil conservation, most of the farm land south of Bamako may merit attention.

The corollary is that most of Mali's farm land north of Bamako does not justify such expense. In these areas, of course, the additional benefits of water-harvesting may make profitable investments that are not justified on the basis of erosion alone.

A second conclusion of this study is that the economic losses resulting from soil erosion may be large enough, in some areas, to render additional investment in agricultural production unprofitable. A project which seemed acceptable under conventional methods of appraisal might easily yield a negative rate of return, if the effects of soil erosion were taken into account. The implication for policy is that we should avoid subsidizing activities and inputs which further deplete the soil. More generally, the probable magnitude of aggregate losses significantly weakens the case for indiscriminate agricultural expansion, while strengthening the argument for increased conservation efforts.

A more frustrating conclusion is that much of the losses taking place are probably excessive; that is, farmers are using up top soil more quickly than we would like. We should not assume that farmers do not know how to conserve the soil, even if certain techniques are foreign to them. It is more likely that they are simply responding to a set of economic, social, and environmental incentives which lead them to deplete the land at a rapid pace.

One reason why farmers may over-exploit the land is the high rate at which they discount future benefits (Appendix G). This suggests certain actions to reduce the time preferences of rural producers, mainly by trying to reduce the risks they face. One option that has been widely discussed is to make rural land tenure more formal, hence more secure. Another approach might be to relax legal and other constraints on providers of informal credit. An expanded supply of rural credit, combined with more certain land tenure, might encourage farmers to invest more in the long term productivity of their land.

More confident prescriptions for policy or programs would require a higher level of confidence about land degradation and its economic impact than this study can provide. Better estimates of soil erosion must await an expanded physical data base, including multi-year field measurements of soil loss in the various regions of Mali, against which to calibrate synthetic predictions. Economic data on farming systems in Mali, comparable to that collected by ICRISAT in Burkina Faso, would also improve the analysis, as would information on how farmers shift their choice of crops and use of inputs, in response to reduced soil fertility.

The weakest link in this study is the relation between land degradation and agricultural productivity. A better understanding of this relation is critical to the evaluation of environmental problems in West Africa. It is a topic especially deserving of additional research efforts.

APPENDICES

APPENDIX A

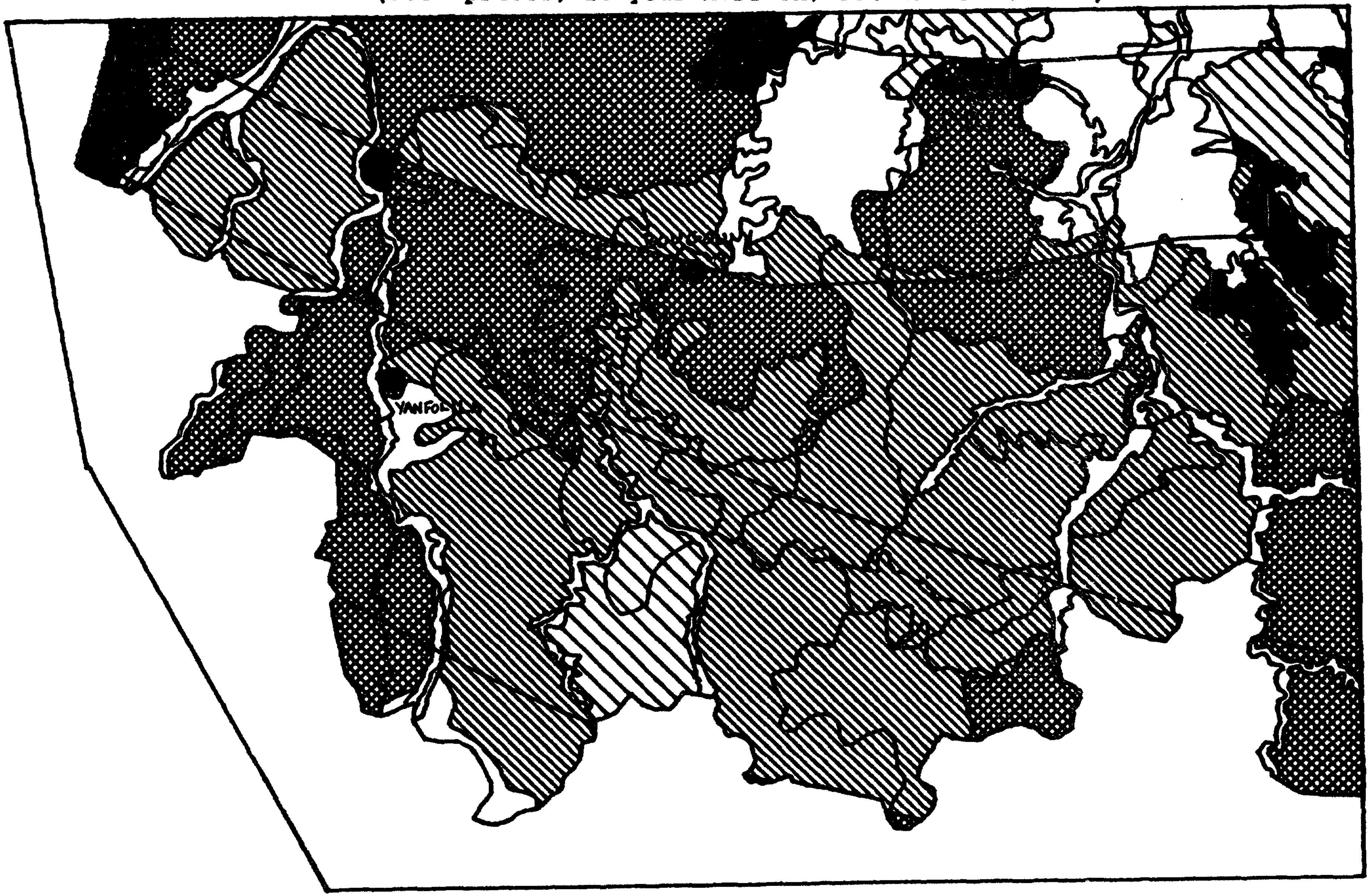
Erosion Losses Relative to the Cost of Conservation

LEGEND

■	BETA = 0.004
▩	BETA = 0.008
▧	BETA = 0.010
▧	BETA = 0.015
●	CITY

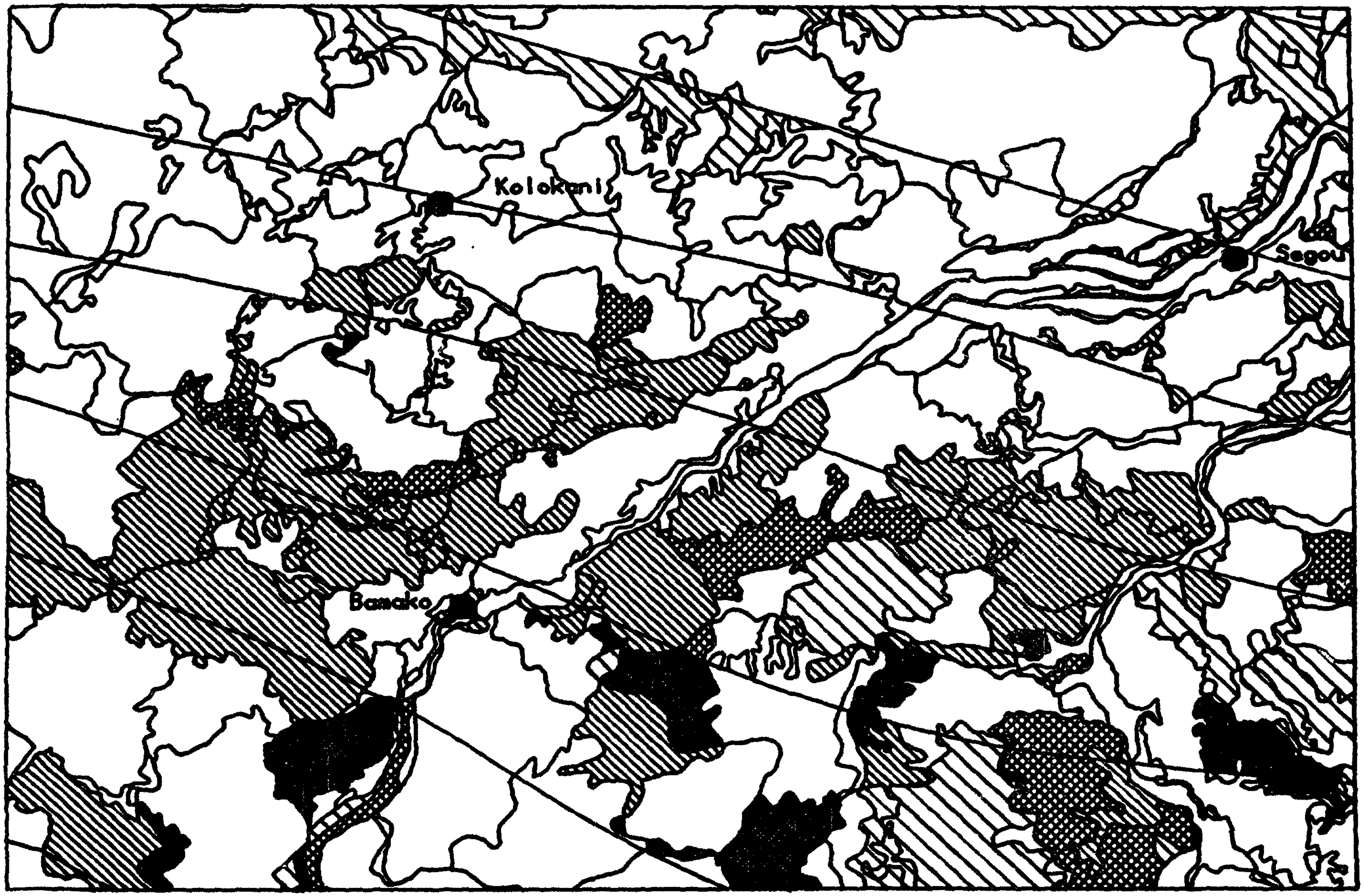
BOUGOUNI : FOREGONE FARM INCOME GREATER THAN 40,000 FRANCS CFA

(1985 prices, 10 year horizon, 10% discount rate)



BAMAKO : FOREGONE FARM INCOME GREATER THAN 40,000 FRANCS CFA

(1985 prices, 10 year horizon, 10% discount rate)



NARA : FOREGONE FARM INCOME GREATER THAN 40,000 FRANCS CFA

(1985 prices, 10 year horizon, 10% discount rate)

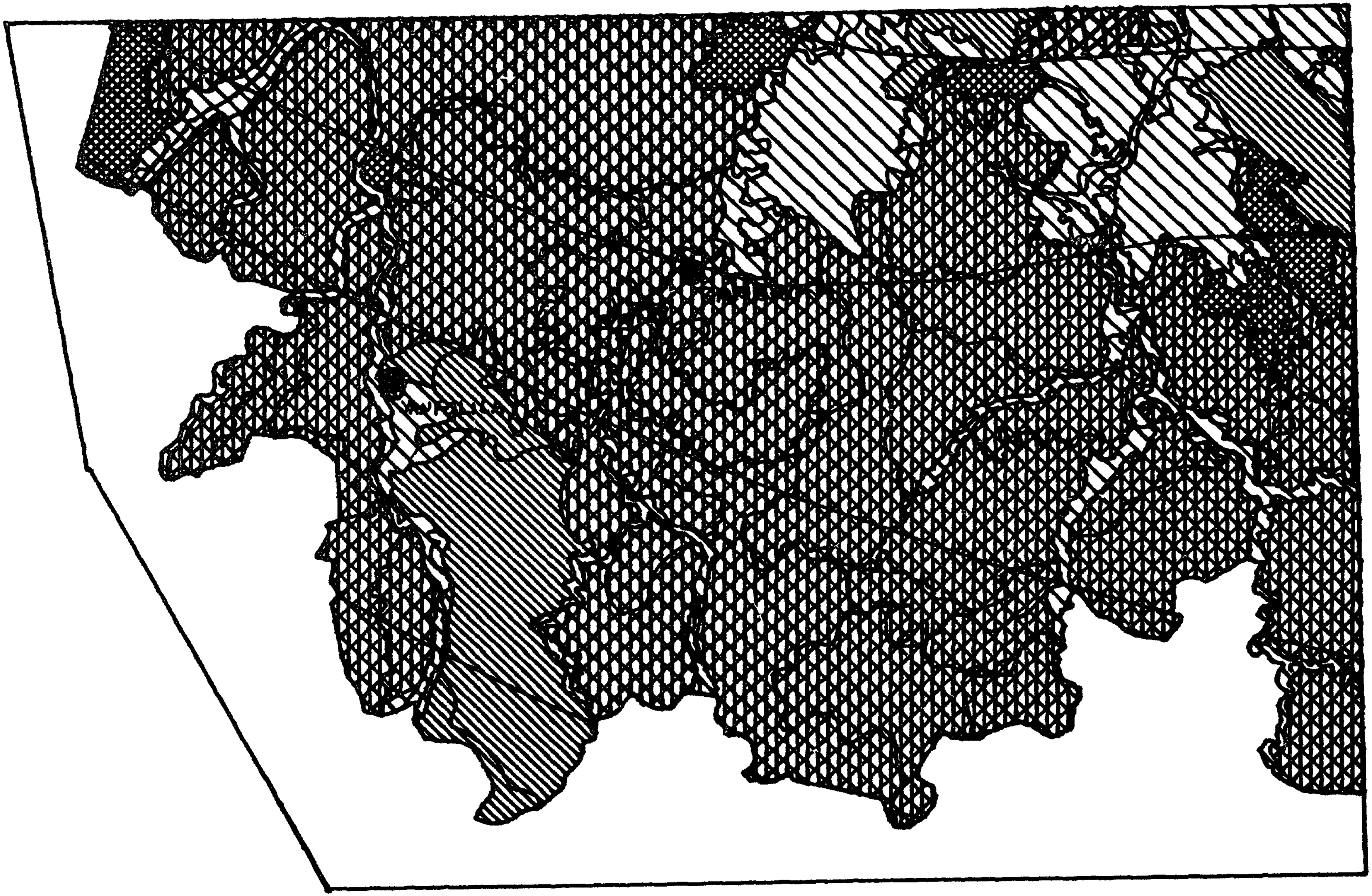
APPENDIX A.1

Estimated Annual Rates of Soil Loss (tons/ha/yr)

LEGEND

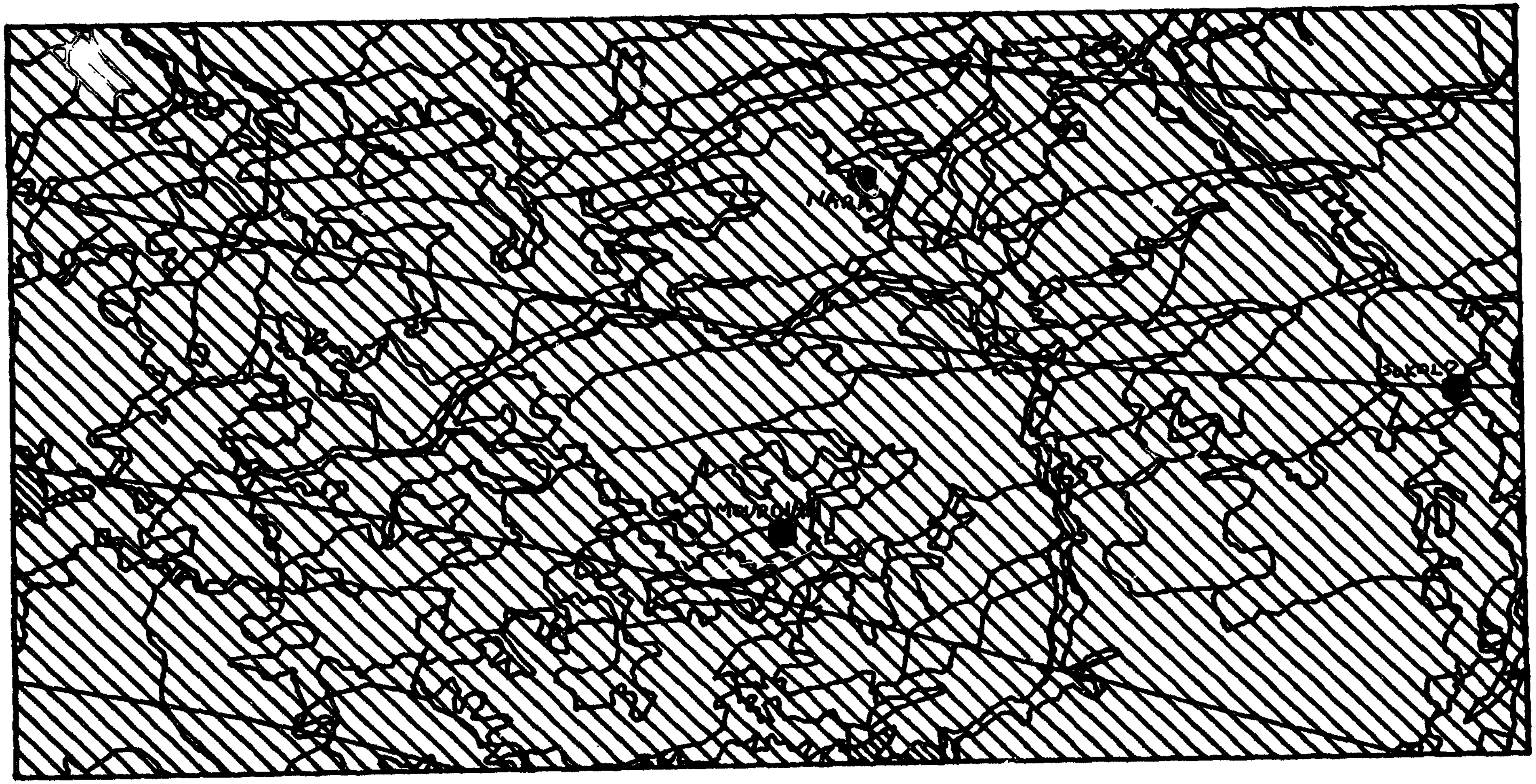
▧	0 <= EROSION <= 4 TONS/HA/YR
▨	4 < EROSION <= 8 TONS/HA/YR
▩	8 < EROSION <= 15 TONS/HA/YR
▦	15 < EROSION <= 25 TONS/HA/YR
■	EROSION > 25 TONS/HA/YR
●	CITY

BOUGOUNI : ESTIMATED ANNUAL SOIL LOSS (tons/ha/yr)



BAMAKO : ESTIMATED ANNUAL SOIL LOSS (tons/ha/yr)

NARA : ESTIMATED ANNUAL SOIL LOSS (tons/ha/yr)



APPENDIX B

The Effect of Erosion on Soil Nutrient Content

We attempted an independent approach to the evaluation of soil erosion in monetary terms, inspired by a study carried out for Zimbabwe (Stocking 1988). This study related erosion to losses of three organic nutrients: nitrogen, phosphorus, and organic carbon. As we saw above, field experiments suggest that soil losses in tons per hectare are a relatively good proxy for losses of nutrients and other soil characteristics favorable to plant growth. Stocking sought to convert soil losses directly into nutrient losses, since the latter could be roughly valued in terms of commercial fertilizer equivalents. The resulting estimated losses for Zimbabwe are striking: 1.5 billion US dollars of losses per year, on all land; 150 million US dollars per year on arable land alone. This works out to about $50/ha/yr on communal farm land.

Our estimates for losses on Malian farm land, using a similar approach, are far more modest. They are comparable, however, to the losses estimated by way of yield effects, provided that we express both in the same terms. Recall our assumption above that the impact of erosion on yields would continue until fallowing. This led us to capitalize yield losses over many years. In contrast, we do not assume that eroded nutrients would have been available to plants more than once. Hence we do not capitalize nutrient losses. This procedural difference accounts for much of the divergence between losses estimated by way of crop yields, and losses derived from the nutrient approach.

1. From Soil Erosion to Nutrient Losses

Stocking's paper relates soil loss, in tons per hectare, to erosion of three organic nutrients: total organic carbon (O.C.), total nitrogen (N), and available phosphorus (P). The relation was established for each nutrient by way of bivariate regression equations, generated from data collected during soil erosion research in Zimbabwe over many years. The relation was found to be reliable ($R^2 > 90\%$), suggesting that soils are fairly uniform across Zimbabwe. The form of the equation is as follows:

$$Y = \beta * X^{\alpha}$$

where : Y = nutrient loss (kg/ha)
β = coefficient varying by nutrient
α = . . .
X = soil loss (kg/ha)

Given the distance between Mali and Zimbabwe, and the possibility that soils are not similar in the two countries, we chose to recalculate identical regression equations, using data from IITA in Nigeria (Lal 1976). As noted above, southwestern Nigeria is also far from Mali, but soil maps of West Africa suggest that the two countries share roughly comparable soils.

The IITA data include the weight of eroded sediments, and of eroded nutrients, under four soil management treatments, on four slopes, over four seasons. Due to the availability of records on losses of exchangeable potassium (K), in addition to the other nutrients measured by Stocking, we were able to add a fourth equation, reproduced with the others, below.

The relation between soil erosion (tons/ha) & nutrient loss (kg/ha)

(based on data from IITA, Ibadan, Nigeria)

Organic Carbon (Y) v. Soil Loss (X)

$\ln Y = 3.096 + 0.938 \ln X$ Adj. $R^2 = 0.94$

$Y = 22.11\ X^{0.938}$ 55 observations

Total Nitrogen (Y) v. Soil Loss (X)

$\ln Y = 1.04 + 0.872 \ln X$ Adj. $R^2 = 0.97$

$Y = 2.83\ X^{0.872}$ 36 obs.

Available Phosphorus (Y) v. Soil Loss (X)

$\ln Y = -3.15 + 1.052 \ln X$ Adj. $R^2 = 0.87$

$Y = 0.043\ X^{1.052}$ 55 obs.

Exchangeable Potassium (Y) v. Soil Loss (X)

$\ln Y = -1.36 + 0.879 \ln X$ Adj. $R^2 = 0.96$

$Y = 0.257\ X^{0.879}$ 55 obs.

These equations are readily compared to those of Stocking by plotting points, for any level of soil loss (figures B.1-B.4). As may be seen from the graphs, regressions based on data from Nigeria predict slightly higher losses of organic carbon and total nitrogen than Stocking's equations, while predicted losses of phosphorus are considerably lower. Presumably this reflects differences in the nutrient content of soils from Ibadan, Nigeria, relative to the average for Zimbabwe.

Figure B.1

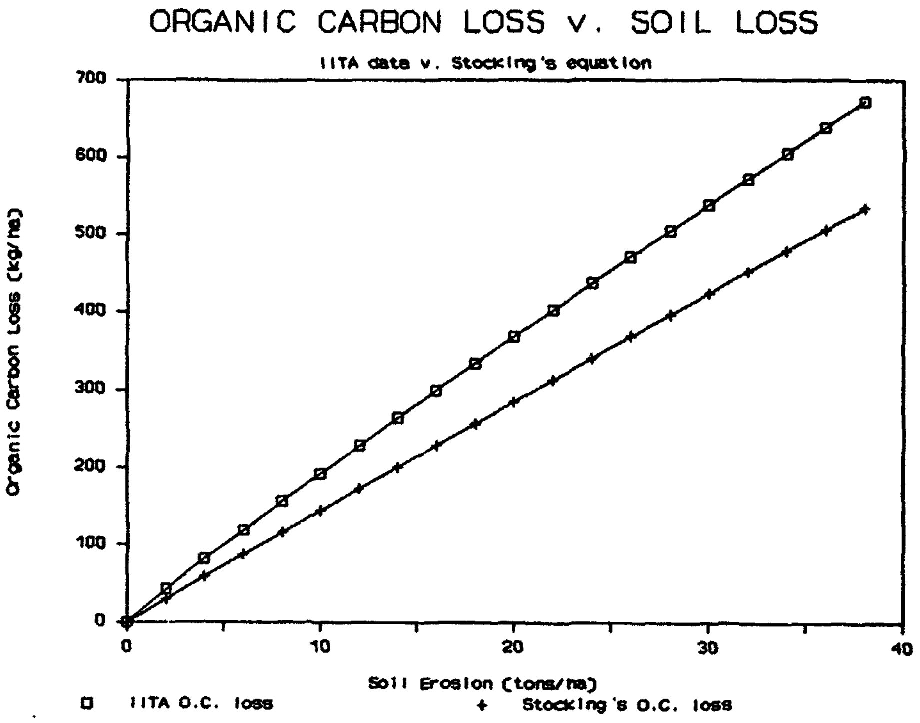


Figure B.2

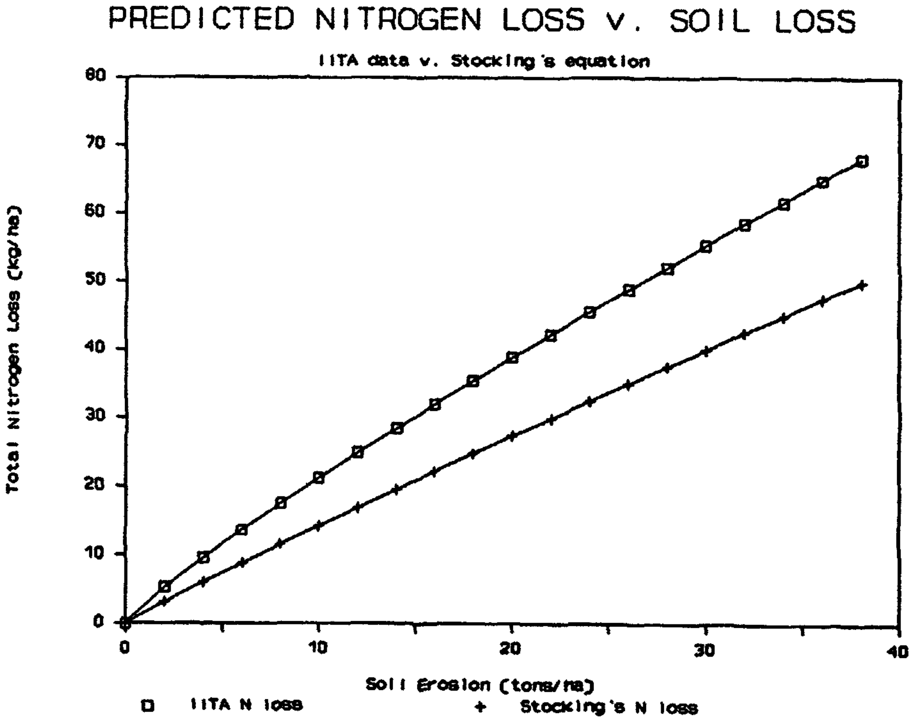


Figure B.3

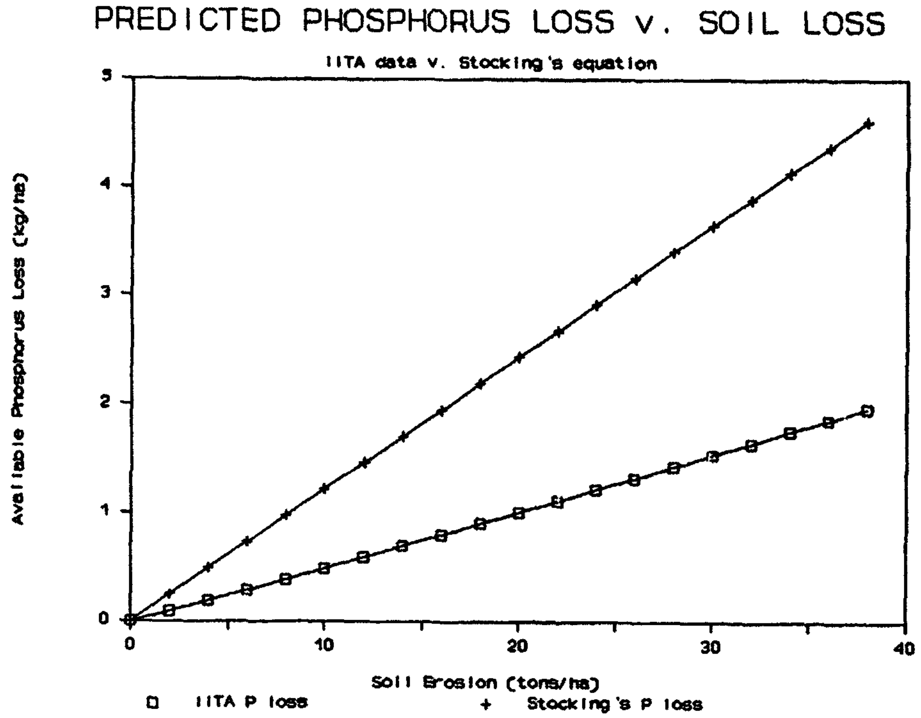
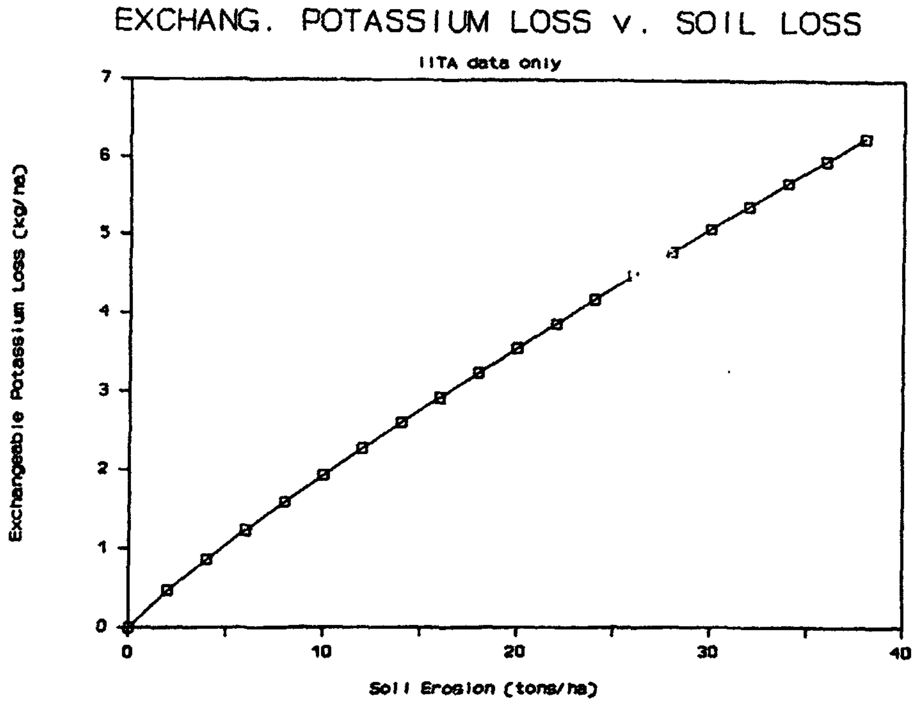


Figure B.4



The mechanics of estimating nutrient losses, and converting those losses into equivalent values of commercial fertilizers, are as follows:

1) estimate the mean rate (t/ha/yr) of soil loss for different types of crop land;
2) estimate nutrient losses (kg/ha) associated with each rate of soil loss;
3) estimate and price ($/ha) the fertilizer equivalents of those nutrients;
4) estimate the total cultivated surface area (ha) subject to erosion;
5) calculate gross losses in national income (in dollars, and as % of GDP).

2. From Nutrient Losses to Fertilizer Equivalents

To translate kilograms/ha/yr of nutrient losses into equivalent weights and values of commercial fertilizer, we must make assumptions about the proportion of eroded nutrients that would have been available to plants, and the nutrient content of typical fertilizers. We then apply current prices (1988), including the cost of delivery to Mali. Nutrient contents and prices are from S. Carr (World Bank, pers. comm. 1989).

As may be seen by inspection of the equations used to estimate nutrient erosion, the total weight of losses is greatest for organic carbon. Following Stocking's example, however, we do not attempt to value O.C. losses in monetary terms. Organic carbon is assumed to be a vital but transient constituent of soil fertility (Lal 1987a, Stocking 1988). The only comparable fertilizer would be manure, which decomposes so rapidly under tropical conditions that it may be misleading to ascribe a monetary value to it.

The second greatest losses, in terms of absolute mass, are of total nitrogen. For the base case, we assume that only 4% of total nitrogen would have been available to plants in any year (Stocking 1988, Nye & Greenland 1960).[6] We therefore discount the portion of eroded nitrogen that would have become available to plants in

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[6] Hobbs et al. (1980) suggest that mineralization of total nitrogen may be as high as 25% per year, in the tropics. In our calculations, using a 10% discount rate, this would increase the present value of _available_ nitrogen losses from about 40% of total annual physical losses to about 87%.

subsequent years. With a 10% discount rate, this has the effect of more than halving the present value of eroded nitrogen.

We then translate tons of "present" available nitrogen lost to erosion, for every map unit, into equivalent weights of Urea, with the assumption that every 100 kg of Urea contains 46 kg of available nitrogen. Finally, we apply a price of US $235/ton (1988), which includes an estimated $65/ton for freight and delivery to Mali.

Similar calculations are carried out for the much smaller estimated losses of phosphorus and potassium. In the first case, based on Stocking's example, we assume that all of the phosphorus lost ("Bray P") would have been available to plants in the same year. We make the same assumption for exchangeable potassium. The respective conversion ratios and prices are: 23 kg P per 100 kg of Triple Superphosphate, at US $243/ton; and 46 kg K per 100 kg of Potassium Chloride, at US $168/ton.

The result of these calculations is the approximate cost of "replacing" the nutrients lost by way of soil erosion on crop land, in each of the TAMS map units. Since these losses vary directly with the rate of soil erosion, we did not generate a separate set of maps showing the value of nutrient losses. We can show, however, the average and maximum value of nutrient losses across the area analyzed, as in Table B.1. Note that the relative proportions of estimated monetary losses made up by N, P, and K are constant at about 77%, 10%, and 13%, respectively.

Table B.1. Annual losses of N, P, & K on cropland

(4% N avail./ yr., r = 10%, 1988 prices, US $1 = 300 CFA)

	Average loss		Maximum loss	
Map sheet	US $/ha	CFA/ha	US $/ha	CFA/ha
BOUGOUNI	5.46	1,638	10.22	3,066
BAMAKO	2.32	696	22.32	6,696
NARA	0.79	236	2.01	603

The average nutrient loss, for the three map sheets studied as a whole, is estimated at US $3.07/ha/yr (CFA 921). To compare this to losses estimated by way of crop yields, however, we need to make another adjustment. We can reduce both approaches to a one year perspective, by considering only the nutrients that would have been available to plants in the current year, and only the effect of the current year's soil loss on current income.

On this basis, the two approaches yield comparable estimates of average losses over the three map sheets studied. Using the nutrient loss equations, and assuming that only 4% of total nitrogen would be available to plants in the current year (100% of P and K), average losses are about US $0.90 per hectare. If we assume that a higher proportion of total nitrogen becomes available to plants in any year, nutrient losses will be higher - $1.60/ha at a 25% mineralization rate. By comparison, using crop yields and farm budgets to determine average current losses, in 1988 prices (US $1 1983 = $1.45 1988), we derive values between $1.00/ha (Beta = 0.004) and $3.92/ha (Beta = 0.015).

In general, when the two approaches are compared over a common time horizon, the value of nutrient losses is lower than the value of yield losses. This may be attributed to the fact that nutrient losses capture only a small part of the total impact of soil erosion. They do not reflect, for example, the deterioration of water holding capacity or soil structure, or the development of surface crusts which impede the infiltration of runoff.

Table B.2. Estimated annual nation-wide nutrient losses

(r = 10%, Avail. N = 4%, est. 1988 prices, US $1 = 300 CFA)

Map Sheet	Map Sheet Loss (CFA millions)	Surface Area (Multiplier)	National Loss (CFA millions)
BOUGOUNI (South)	395	1.25	494
BOUGOUNI (North)	238	1.25	297
BAMAKO (South)	224	2.83	633
BAMAKO (North)	173	3.48	603
NARA (South)	32	3.50	112
NARA (North)	20	4.35	86
			2,225

	US Dollars (Millions)	Francs CFA (Millions)	% Mali GDP*	% Agr. GDP**
Nationwide Annual Nutrient Losses on Farm Land :	7.41	2,225	0.37	0.95

* estimated from 1987 data: GDP = 572 Billion CFA; inflated 5.5%

** includes only farming; estimated from 1984 data; contrib. to GDP from trad'l. & mod. agr. = 174 Billion CFA; inflated 35%

Table B.2 (above) presents estimated annual gross national nutrient losses, in the same format as we presented aggregate foregone farm income losses (Table 12, pg. 19). Table B.3, below, presents a range of gross national nutrient losses from annual soil loss, under different assumptions. We vary the proportion of total nitrogen that is mineralized, i.e., available to plants in the current year, as well as the discount rate applied to the eroded nitrogen that would have been mineralized in subsequent years.

Table B.3. Sensitivity analysis: nation-wide nutrient losses

(% of estimated 1988 agricultural GDP*)

Discount Rate	% of total nitrogen mineralized		
	4%	10%	25%
15%	0.76	1.28	1.73
10%	0.95	1.46	1.83
5%	1.30	1.71	1.94

APPENDIX C

Current Theories and Recent Examples of Natural Resource Accounting

Natural resource economics is often associated with the determination of optimum extraction rates for non-renewable resources, such as petroleum and minerals. Additional issues that occupy natural resource economists include the pricing of non-traded resources, the relation between tenure over resources and their depletion, and the environmental effects (externalities) that result from use of natural resources.

At the level of project appraisal, appraisal of environmental effects is still far from routine. This is partly because environmental impacts are often subtle, slow to reveal themselves, and difficult to measure. We also cannot exclude the incentive for project managers to underestimate the environmental costs of activities they supervise, particularly as those costs are rarely internalized by the agency funding or supervising the project.

The benefits of resource conservation are also difficult to quantify, and rarely documented, particularly in the Tropics. What research that has been carried out is invaluable to the selection of appropriate technical responses to environmental problems, but does not help us decide where there is a problem, or if indeed conservation is the least cost alternative.

At the level of national, or macro-economic accounting, attempts to reflect environmental phenomena have engendered considerable controversy. Conventional measures of national income and economic performance, such as the Gross Domestic Product, and the Current and Capital Accounts, have been widely criticized for inadequately reflecting the depletion of natural resources.

Industrial pollution provides a classic example of how macro-economic indicators may be distorted by environmental impacts. One exposition [Repetto et al. 1987] succinctly describes the perverse effects of conventional practices of national accounting:

> "If toxic substances leak from a dump site to pollute soils and aquifers, measured income does not go down, despite possibly severe impairment of vital natural resources. If the government spends millions of dollars to clean up the mess, measured income rises, *ceteris paribus*, because such government expenditures are considered to be purchases of final goods and services. If industry itself undertakes the cleanup, even if under court order, income does not rise, because the same expenditures are considered to be intermediate production costs if carried out by enterprises. If the site is not cleaned up, and nearby households suffer increased

> medical expenses, measured income again rises, because household medical expenses are also defined as final consumption expenditures in the national income accounts" (pg. 18)

It is thus argued that measures of current economic performance should be adjusted to account for depletion of, or damage to, renewable and non-renewable natural resources. Otherwise, it is claimed, economic performance will be over-stated by the amount of the uncounted damage or depletion. The result is to send over-optimistic signals to decision-makers, who consider GDP growth an indicator of economic progress. Policy decisions regarding the allocation of public resources may be taken under false assumptions of their long-term costs.

Economists disagree on how to include the depletion of natural resources in the system of national accounts. In a review of recent papers, El Serafy and Lutz (1989) identify two major conceptual approaches: the depreciation and the 'user cost' approach. Both end up deducting, from current income, some estimated value for the loss incurred by depletion of natural assets. A brief description of each approach, and examples of recent applications, are presented below.

1. The Depreciation Approach

The depreciation approach to natural resource accounting applies the principle of depreciation of man-made capital to renewable and non-renewable natural resources. Resource stocks are estimated in physical terms and evaluated in monetary terms. Net changes are tabulated for each accounting period, and deducted from income. The result is to shift attention from gross measures of national income (GDP) to net measures (NDP).

Critics point out that: i) a true measure of net national income would essentially negate the real revenue advantage of exploiting natural resources, ii) correctly pricing resources is not obvious, iii) consistency requires the deduction of such major spending categories as national defense and health care and, iv) most policy-makers pay attention to measures of gross income, hence resource economists should also.

A recent example of the depreciation approach may be found in a study of resource depletion in Indonesia (Repetto et al., 1987), where both natural forest reserves and petroleum deposits were considered as capital assets. Evaluation of stocks in monetary terms was straightforward, as both petroleum and timber are internationally traded goods. In the case of forests, only the benefits from timber production were counted.[1]

The methodology used is based on the creation of physical accounts for stock levels, and for changes from various causes in each accounting period. In the case of forest resources, changes in stock levels include natural growth and planting, deforestation by man and natural degradation, and extraction of timber. In the case of petroleum deposits, discovery of new reserves is incorporated as positive growth in stock levels, while pumping draws them down. Note that the model fails to distinguish between an efficient and an inefficient rate of resource extraction.

The model uses net average pricing, to correct for changes in the market price of resources over accounting periods. This simply requires a revaluation adjustment at the end of each accounting period, recorded as an unrealized capital gain, and with no impact on income.

Over a twelve year period (1970-1982), the authors found a significant difference between GNP growth as currently calculated, and as corrected for depletion of forest and petroleum reserves. The average annual growth rates of the two series differ by 2.5 percent per year. If not for the discovery of major new petroleum deposits, the gap would have been far wider.

2. The User Cost Approach

The user cost approach to natural resource accounting avoids an explicit calculation of net income. It is based on the idea that revenues from the sale of a depletable resource, net of extraction costs and any externalities, can be split into a capital element or user cost, and a value-added element representing true income. User cost represents asset erosion, or the opportunity cost of not being able to exploit the resource at some later date. It is equal to the discounted present value of forgone future benefits from use of the resource. User cost is the portion of revenue derived from depleting an asset which should, hypothetically or in fact, be reinvested in order to maintain a perpetual income stream.

The user cost approach is typically used to determine optimal rates of extraction for non-renewable resources. If extraction is too slow, it is argued, the unit price of remaining stocks will tend to decline, relative to prices of other goods. Hence the rate of return on holding stocks of the resource will be low, creating

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[1] Had the authors included the value of forests as a source of meat and fruit, for example, the net deduction from gross income would have been greater.

an incentive to cash in and convert the proceeds to some higher yielding use. Conversely, if extraction is too rapid, the unit price of remaining stocks will rise quickly. This creates an incentive to hold the resource, which offers a higher rate of return than other assets. The "natural" equilibrium rate of extraction is such that the price of the resource will rise at the rate of discount, i.e. the rate of return on alternative assets.

This argument has been developed in the context of national income accounting by Devarajan and Weiner (1988), among others. The point is that resource extraction does not necessarily involve any economic waste. An efficient rate of resource depletion exists which may be higher or lower than actual rates. Inefficient exploitation may occur if there are significant externalities associated with the use of a resource, which are not reflected in the market price. Alternatively, we may determine that resource use is non-sustainable if the proceeds of extraction are not reinvested in other income yielding assets. In the latter case it is not the depletion *per se* that is problematic, but the use made of the wealth gained thereby.

Two recent studies which adopt a user cost approach are: Pearce and Markandya (1985), on deforestation in the Sahel, and Magrath and Arens (1987), on soil erosion on Java. Both studies attempt to monetize direct costs and externalities. The first study looks at the effects of deforestation on energy sources, water supply and agricultural output; the second paper considers the effects of soil erosion on crop productivity and sedimentation of reservoirs and harbors. Only the study of Java, however, attempts to calculate a global cost in terms of GNP.

A. Deforestation in the Sahel

Pearce and Markandya adopt a marginal pricing approach, within a framework of discounted cost-benefit analysis. They assert that estimating the marginal cost of a depletable but *tradeable* resource is non-controversial, in an efficient market. Like Repetto et al., they maintain that the appropriate shadow price of a tradeable resource is simply its 'border price'. This assumes, however, that the resource, if and when depleted, may be replaced by imports.

In this case, the social opportunity cost of exploitation is readily determined, and is equal to the border price of a resource minus the marginal extraction cost. This relation permits a direct calculation of optimum extraction rates, based on the rule that the value of a resource stock, under optimum extraction, must grow at the discount rate.

Many developing countries, however, have limited options for the import of substitutes for critical natural resources. Lacking an alternative source of revenue, they cannot afford to lose their natural forests, soil fertility, and ground water, for example. Pearce and Markandya argue that because such assets are not replaceable, they are effectively non-tradeable. In such cases, where the relevant shadow price is unavailable, the authors propose a more complicated procedure to estimate the marginal opportunity cost of exploitation. Their model attempts to account for the fact that:

> "Any resource using activity will involve direct 'extraction' costs, a foregone benefit to future users (since less will be available to them) which is the 'user cost' component, inter-sectoral costs in the form of externalities (e.g. deforestation's impact on soil erosion and water supply), and a future cost in terms of increasing the magnitude of any 'disaster' which has as its imminent cause some exogenous shock (lack of rainfall, etc.)" (pg. 12).

Applying the model to Sahelian forests, the authors combine all of these different costs in an estimate of the marginal opportunity cost (MOC) of deforestation arising from fuel wood consumption. They do not come up with a single figure for the Sahel as a whole, but rather calculate a range of values for MOC, expressed as a proportion of the cost of the backstop technology.

Pearce and Markandya also discuss at length the choice of an appropriate social discount rate, which has a significant effect on the calculation of marginal cost. They review a number of arguments for using high discount rates where low income groups are concerned, but also note that this will reduce the estimated marginal cost of exploiting natural resources. This occurs because both user cost and the inter-sectoral components of MOC are long term effects, which are negated by high discount rates.

B. Soil Erosion on Java

Magrath and Arens, in their study of the costs of soil erosion on Java, devote less attention to theoretical issues. They attempt to derive a single plausible figure, rather than to explore the dynamics of their model. They also make no attempt to determine the stock of arable soil. The analysis is based instead on estimates of current *rates* of soil erosion (in tons/ha/yr), and attempts to quantify two effects thereof: reduced crop yields, and increased sedimentation of reservoirs and harbors. In effect, they consider what Pearce and Markandya external cost (inter-sectoral effects), and user cost (i.e., replacement or substitution), but they ignore direct cost (extraction) and 'disaster' cost.

Magrath and Arens' analysis builds on a physical assessment of rates of soil erosion, based on extrapolation from scattered runoff plots. While they do not explicitly apply the Universal

Soil Loss Equation (USLE), they do consider soil type and slope, rainfall erosivity, and land use in their estimation of local rates of erosion. The methodology is straight-forward, but involves a number of tenuous steps to arrive at an estimate of the impact of soil erosion on national income.

> "The size of areas equally susceptible to erosion are quantified. Estimates of these levels of erosion and ... of the impact of these levels on crop yields are then combined with data on the predominance of alternative upland farming systems. This yields estimates of reductions in agricultural output due to erosion. Representative farm budgets are used to value those changes" (pp. 2-3).

As noted above, the agricultural impacts of soil erosion are combined with estimates of the "major off-site or downstream costs, ... [eg:] reservoir and irrigation system siltation and siltation of harbors and waterways" (pg. 3).

According to their calculations, the on-site costs of soil erosion, in terms of reduced crop yields, far outweigh the costs of increased sedimentation. Lost agricultural production due to soil erosion is estimated at roughly 4%. Since agriculture contributes only modestly to Java's GNP, however, the net effect of erosion on national income remains small.

The analysis builds on six sources of data, listed below:

1. FAO soil map (1959), scale 1:1,000,000; combining soil units with topography and distinguishing 25 units:

   5 units of soil w/ slope < 8%;
   11 units of soil w/ slope 8 - 30%;
   9 units of soil w/ slope > 30%.

2. Bols erosivity map (1978), scale 1:1,000,000; correlating kinetic energy of storms with annual rainfall: 11 classes of erosivity.

3. Ministry of Forestry land use map (1985); distinguishing 5 types of land use or vegetation cover:

   - 'sawah' (low erosion or sedimentation);
   - 'tegal' (dry land farming on sloping uplands);
   - forest (natural or planted perennial);
   - degraded forest (shifting cultivation);
   - wet lands.

4. Experimental data on actual erosion rates under varying plant cover or cropping, (UNDP/FAO, USAID, etc.); used to estimate erosion rates for 'different soils under the influence of prevailing rainfall erosivity and under the major types of land use described'.

5. 'Scanty data available from controlled experiments,' used to estimate productivity loss - erosion relationships (in % yield loss for a given range of soil loss) for the 25 soil types considered and for two groups of crops:

   - relatively sensitive crops (maize, soybean, groundnut, green bean, dry land rice);
   - relatively insensitive crops (cassava).

6. 'Farm level data from a variety of sources,' used to develops sets of enterprise budgets (including fixed and variable costs, etc.) representative of the range found in Java's uplands.

APPENDIX D

Mali Land and Water Resources: A description of the data contained in the atlas prepared by Tippetts, Abbett, McCarthy, and Stratton (TAMS), 1983.

1. Rainfall

The TAMS atlas includes maps showing average annual rainfall, computed from multi-year precipitation records at stations throughout the country. The information is displayed in conventional format, by drawing isohyetes for every 100 mm interval of average precipitation. The isohyetes are roughly parallel from East to West, showing increasing rainfall as one moves south, away from the Sahara desert. Additional information on ground water is not used here.

2. Soil and vegetation

TAMS soil and vegetation maps distinguish 68 units of association in ten broad groups that share major characteristics. Each group comprises units with common physiographic and/or soil features. The relative importance of the ten groups is shown in Table D.1. Due to the large scale of the atlas, individual map units typically include two or more associated soil/vegetation classes. The relative prevalence of each class within every map unit is indicated on the atlas, in percent of total surface area.

The soil/vegetation units are described in detail in Volume II of the TAMS atlas. Information used here includes the typical uses, and the range of slope gradients associated with each soil/vegetation unit. The atlas notes which units are used exclusively or predominantly as pasture, those which are cultivated, and the relative intensity of cultivation (i.e. continuous, occasional, or only with a long fallow period).

Topographic information is more limited, with a wide range of slopes ascribed to certain soil/vegetation units. Five ranges of slope are used to rank map units: "flat to almost flat" (0-2%), "gently sloping" (2-6%), "sloping" (6-13%), "moderately steep" (13-25%), and "steep" (25-55%). TAMS identifies 18 of the 68 map units, covering 37% of the total study area, with slopes over 6%. Eleven of these units (23% of the study area), however, consist of dunes in the North of Mali, and are only occasionally used for millet farming. On more regularly cultivated land, slopes rarely exceed 6%.

Table D.1: Surface area of Major Soil/Vegetation Groups

Soil/Vegetation group	Surface area (sq. km.)	Percent of total TAMS study area
Stable dunes	100,378	17.2
Eroded dunes	58,089	10.0
Plains of clayey material	12,656	2.2
Plains of silty & loamy material	92,140	15.8
Plains of loamy material	21,410	3.7
Hydromorphic lands, not flooded	19,657	3.4
Flooded lands	26,203	4.5
Rocky lands	43,912	7.5
Lands underlain by laterite	123,854	21.3
Special land types	34,259	5.9
Inclusions	50,220	8.6
TOTAL	582,778	100.0

3. Land Use

Additional information on land use is presented in a separate set of maps. Individual units are distinguished by the type, site, distribution and density of land use; the crops grown in order of importance; and the species of livestock grazing each separate map unit. Not surprisingly, there is a close correspondence between the map units demarcating soil and vegetation resources, and those identifying land use.

Nine possible types of land use are recognized, within five general classes: pastoral, agro-pastoral, agricultural, bush pasture (i.e., devoid of human settlement and not within pastoral grazing areas), and unused (comprising only one unit of inaccessible plateau, in the far West of Mali). Note that because we do not consider soil erosion on rangeland, we did not encode any of the data on pastoral land use for this study.

Generally each map unit will correspond to a unique type of land use or site. Where an additional land use type or site is important, within a unit, the atlas designates inclusions. This occurs frequently in the south of Mali, where rain fed cultivation is dominant, but scattered throughout is irrigated farming (principally rice) in small, seasonally-flooded depressions.

To account for the fact that particular land uses do not always occur evenly throughout a map unit, the atlas distinguishes 17 types of agricultural sites. The atlas further distinguishes three possible patterns of distribution of agricultural land use: continuous (contiguous fields), discontinuous (resembling beads along a string), and dispersed (scattered fields separated by non-agricultural land). Twenty principal crops are recognized. For each land use unit, the atlas shows the dominant crops grown, with the first three listed in descending order of importance.

Four categories of agricultural density refer to the percentage of cleared or cultivated land within a map unit. The ranges are 0 - 10%, 11 - 30%, 31 - 60%, and above 60%. For the purposes of this study, we adopted average values of 5, 15, 45, and 80%, respectively. On this basis, the average agricultural density in the study area (BOUGOUNI, BAMAKO, NARA) is only 12%, with a maximum of 16% in the Sudanian zone and a minimum of 8% in the Sahelian zone.

Both recently fallowed and cultivated fields are combined in this measure of density, as the two are virtually indistinguishable on LANDSAT images (Vol. II, D-11). Field surveys conducted by the TAMS team revealed no consistent fallow period. In southern Mali, for example, fields adjacent to villages often undergo continuous cultivation, due to the relative ease of transporting manure and other organic fertilizers. More distant fields may be fallowed less than five years or more than twenty, depending on availability of inputs, population pressure, and other local conditions.

For this study, we assume a uniform crop-fallow ratio of one-to-one. In other words, 50% of the cleared or cultivated land identified by TAMS is assumed to be sown in any year. This assumption is based on observations in Mali by recent World Bank missions (Bremen et al. 1988), and on data collected in the preparation of crop budgets in Burkina Faso (Matlon & Fafchamps 1988). If the assumption is correct, we would conclude that the total surface area cultivated in any one year will account for 4 to 8% of all available land.

This range is higher than densities suggested by recent statistics on agricultural production in Mali. The World Bank (Levine 1983) reports a total of 1.8 - 2.0 million hectares under cultivation, in the period when the TAMS atlas was prepared (1979-80), which comprises less than 4% of the surface area receiving over 200 mm annual rainfall. Our manipulations of the TAMS atlas imply a total cropped surface area of about three million hectares. On the other hand, some authors consider the official statistics on crop acreage to be underestimated, at least in Mali's southern regions (Bremen & Traoré 1987).

APPENDIX E

The Universal Soil Loss Equation and Soil Deposition

The argument for modifying the USLE arises from the fact that the model ignores soil deposition and thus, when applied on a large geographic scale, it systematically over-estimates soil loss (Stocking 1984). While USLE estimates of soil loss may be accurate for specific locations, other areas are gaining soil. Current estimates suggest that only 5 - 10% of eroded soil reaches the major rivers (Walling 1984). Thus 90 - 95% of the soil loss occurring on upland plots is redeposited somewhere down-slope, along the watershed.

The question is, where is the soil redeposited? Some light is shed by measurements carried out on vastly different scales for three separate studies of soil erosion in the Ader Dutchi massif of Niger (mean annual rainfall = 400 mm). On a 0.34 ha plot at Allokoto, under traditional cultivation, measured soil losses from 1967-71 varied from 3.5 - 18.5 t/ha/yr (Delwaulle, 1973). On a cultivated watershed of 3.5 ha near Kountkouzout, with comparable slope and soil type, sediment load measurements from 1965-67 revealed soil losses of 12 - 13 t/ha/yr (Vuillaume, 1982). When sediment load measurements were made on the neighboring 117 km2 Ibohamane basin, from 1969-75, total soil loss was found to average 40 t/ha/yr (Heusch, 1980). 56% of the latter was found to result from erosion of gullies and stream banks, implying that sheet erosion averaged 17.6 t/ha/yr throughout the basin.

All of these measurements fall within the same order of magnitude, from plots of less than a hectare to over 100 square kilometers. When we move to the next level of study, however, soil loss falls dramatically. Sediment load measurements carried out on major rivers throughout West Africa reveal net soil loss on the order of 0.1 - 2 t/ha/yr (Table E.1). This implies that most eroded soil is deposited in large natural "sinks," or in man-made reservoirs.

If we assume that the measurements made in Niger are applicable to Mali, then we might conclude that the USLE estimates of soil loss are accurate for all but the largest floodplains and depressions. In that case, little adjustment of the model would be required, except in a few strategic spots, such as the Inner Delta of the Niger.

Table E.1. Sediment load for selected African watersheds

Sediment load (t/ha/yr)	Country	River	Catchment (km2)	Source
0.13-0.47	Senegal Mali Gambia	Senegal Niger Gambia	?	ORSTOM, personal communication
0.331	Senegal Guinea Niger Mali Nigeria	Niger	1,114,000	Milliman and Meade, 1983
0.85	Cameroon	Mbam	42,300	Olivry, 1977
0.28	"	Sanaga	77,000	"
2.1	"	Tsanaga	1,535	"
1.55-4.38	Nigeria	4 rivers	Sokoto basin	Oyebande, 1981
2.19-7.39	"	5 rivers	Hadejiia-Jamaare basin	"
0.2-0.8	Nigeria	"major rivers"		"
40	Niger	Ibohamane	117	Heusch, 1980
0.094	C. I.	Amitioro	170	Mathieu, 1971
0.039	Chad	Chari	600,000	ORSTOM, personal communication
0.149	"	Logone	85,000	"
4.5	Nigeria	Niger	1,113,000	Lal in Lal et al., 1986

From D.E. Walling, "The sediment yields of African rivers" in D.E. Walling, S.S.D. Foster, & P. Wurzel (eds.) Challenges in African Hydrology and Water Resources (Proc. Harare Symposium, July 1984). IAHS Publ. no. 144.

For the present study, we simply set the soil erodibility parameter (K) equal to zero for all soil types subject to high rates of deposition, according to the soil/vegetation unit descriptions in volume II of the TAMS atlas (pp. B-41 to B-61). This accounts for 19 of the 68 soil-vegetation units defined in the Mali atlas, or 12.7% of the total surface area (Table E.2). In fact, many of these units are receiving sediment from upstream or up-slope, of which only part is deposited and part passed on. Some may lose more soil than they receive, through gullying and scouring of stream beds. Without better data than are available, however, it is impossible to estimate the rate of deposition, let alone the effects of deposition on crop productivity.

Table E.2. TAMS Soil/Vegetation units subject to soil deposition

	Rate of soil deposition			
Soil group	low	(% of area)	high	(% of area)
Eroded dunes:			DA3	1.1
Plains of clayey material:			PA1	1.2
			PA2	0.3
			PA3	0.6
Plains of silty & loamy material:	PL4	1.1	PL3	0.3
	PL5	2.1	PL8	0.9
	PL6	0.5	PL12	0.2
	PL7	0.7		
	PL9	2.2		
Plains of loamy material:			PS1	1.6
Hydromorphic lands, not flooded:	TH2	0.8	TH1	0.2
	TH4	0.3	TH3	0.8
	TH7	0.3	TH5	0.3
			TH8	0.4
Flooded lands:	TI7	0.4	TI1	1.5
			TI2	0.4
			TI3	1.6
			TI4	0.4
			TI5	0.1
			TI6	0.4
Rocky lands:	TR2	1.7		
Special land types:	X1	0.1	X6	0.4
TOTAL AREA (%)		10.2		12.7

APPENDIX F

Farm income, surface area and crop budgets

(based on Matlon & Fafchamps 1988)

1. ESTIMATED GROSS NATIONAL AGRICULTURAL INCOME

Traditional and modern agriculture,
1983 prices, US $1 = 300 CFA,
1979-80 cropping patterns.

Map Sheet	Gross Income (CFA millions)	Comparable Regions	National Income (CFA millions)
BOUGOUNI (South)	5,664	1.25	7,080
BOUGOUNI (North)	4,084	1.25	5,105
BAMAKO (South)	24,683	2.83	69,853
BAMAKO (North)	12,667	3.48	44,081
NARA (South)	4,338	3.50	15,183
NARA (North)	2,890	4.35	12,570
			153,872

	US Dollars (Millions)	Francs CFA (Millions)	% Mali GDP	% Agr. GDP
Gross National Farm Income (trad. & modern agr.)	513	153,872	36.49	98.38

2. SURFACE AREA AND DENSITY OF FARMING IN MALI

(based on 1979-80 survey data)

	STUDY AREA	BOUG (S)	BOUG (N)	BAMAKO (S)	BAMAKO (N)	NARA (S)	NARA (N)
SURFACE AREA ALL MAP UNITS (km2)	187,775	36,041	29,136	35,953	34,721	25,263	26,660
AREA OF MAP UNITS CROPPED/CLEARED	127,185	27,346	18,238	24,750	25,602	14,733	16,516
WTD AVG DENSITY OF CROP/CLEAR (on map units cropped/cleared)	18.45%	16.47%	17.70%	23.39%	21.99%	15.28%	12.51%
PERCENT TOTAL AREA CROPPED (1:1 crop-fallow ratio)	5.39%	6.25%	5.54%	8.05%	8.11%	4.46%	3.88%
STUDY AREA CROPLAND (km2)	11,735	2,253	1,614	2,894	2,815	1,126	1,033
COMPARABLE SURFACE AREA		1.25	1.25	2.83	3.48	3.50	4.35
ESTIMATED NATIONAL CROPLAND (km2)	31,255	2,816	2,018	8,191	9,795	3,940	4,495
WORLD BANK ESTIMATE (1980)	18,640						

3. CROP BUDGETS (based on Matlon & Fafchamps, 1988)

In calculating erosion impacts, we assume that labor for weeding and harvesting is a variable input, which farmers will adjust in proportion to yields. The household wage assumption is 50% of the prevailing regional wage (see Matlon & Fafchamps, pg. 45). All expenditures and revenues in 1983 Francs CFA per hectare.

	SAHEL	SUDAN	N. GUINEA
SORGHUM			
Price (CFA/kg)	60	66	46
Crop value	20,820	38,874	19,964
Fixed non-labor	1,405	1,731	578
Fixed labor	2,104	1,823	4,824
Variable labor	11,051	6,741	5,789
Return to land	6,260	28,579	8,773

	SAHEL	SUDAN	N. GUINEA
MILLET			
Price (CFA/kg)	53	62	52
Crop value	17,755	25,544	17,680
Fixed non-labor	477	994	328
Fixed labor	668	1,408	4,612
Variable labor	7,542	6,364	5,296
Return to land	9,068	16,778	7,444
MILLET & COWPEA			
Price (CFA/kg)			
Millet	?	62	52
Cowpea	?	84	103
Crop value	19,959	21,356	12,933
Fixed non-labor	477	1,337	873
Fixed labor	1,022	1,712	2,312
Variable labor	8,614	4,671	5,585
Return to land	9,846	13,636	4,163

Sahel budget constructed from incomplete data; fixed costs and prices assumed similar to millet.

MAIZE			
Price (CFA/kg)	88	93	29
Crop value	22,352	122,016	29,029
Fixed non-labor	2,765	5,161	8,250
Fixed labor	12,227	6,206	9,946
Variable labor	5,312	4,766	5,401
Return to land	2,048	105,883	5,432

	SAHEL	SUDAN	N. GUINEA
GROUNDNUT			
Price (CFA/kg)	112	112	125
Crop value	21,504	35,056	45,500
Fixed non-labor	16,007	22,788	9,671
Fixed labor	1,538	2,954	3,713
Variable labor	1,493	7,539	15,979
Return to land	2,466	1,775	16,137

Sahel budget based on 10% household wage assumption, to ensure positive returns.

	SAHEL	SUDAN	N. GUINEA
COTTON			
Price (CFA/kg)			62
Crop value			47,306
Fixed non-labor			6,588
Fixed labor			2,983
Variable labor			14,533
Return to land			23,202

Only budget available for the Northern Guinea zone, used in all zones.

	SAHEL	SUDAN	N. GUINEA
RICE			
Price (CFA/kg)			154
Crop value			180,642
Fixed non-labor			7,258
Fixed labor			7,395
Variable labor			18,569
Return to land			147,420

Only budget available for the Northern Guinea zone, used in all zones. (for calculating Agr. GDP)

APPENDIX G

Soil Erosion and Time Preference

Some rate of soil depletion is justified just on the basis of simple time preference (ie: discounting future benefits). It is safe to assume, however, that the range of discount rates used in project evaluation by the Malian government, or by foreign aid agencies, are significantly lower than the implicit rates of discount used by individual farmers in their decision-making.

Evidence from studies of interest rates charged by merchants and other rural lenders in West Africa suggest that the farmer's nominal cost of capital is between 50 to 150% (Shipton 1987). Informal rural lenders may be obliged to charge such high interest rates, due in part to the scale of their operations, and the extreme dependence of the rural economy on subsistence farming. These circumstances prevent creditors from spreading their loans across areas and activities wide ranging enough to compensate for the frequent local droughts typical of the Sahel. If they could offer credit to farmers at lower rates, the latter might be more willing to make long term investments in their land, including soil conservation. The implication, however, is that current rates of soil loss are probably excessive, since farmers will discount future income more than would a social planner.

Another possible cause of excessive rates of erosion is the fact that land tenure in Mali is not very secure (Gorse & Steeds 1987). As in most Sahelian countries, rural lands in Mali are held in common, under traditional systems of tenure. The Malian state generally recognizes only usufruct rights over land, except where it has formally granted free hold title (mostly in urban areas).[1]

Because the state has not formally recognized traditional land management, farmers cannot be certain of long-term access to the land. It is thus argued that farmers will discount the future benefits of land husbandry at an excessive rate, leading them to

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[1] In practice, public administrators may recognize (and often arbitrate) the traditional claims of neighboring communities to permanent land tenure. In such cases, the state's agents may uphold a community's right to prior use (e.g., rights of first access to seasonal pasture), or its power to allocate land use rights among users. Moreover, while the state does not officially invest traditional land managers or users with the right to sell or to sub-lease public lands, a lively clandestine trade in land use rights has been documented in some areas. Because such transactions are illegal, however, it is extremely difficult to determine the extent of the market in land use rights, or the range of prices.

deplete the land in order to maximize present income. Recent drought conditions and increasing rural poverty are added disincentives.

We do not have the data required to determine what portion of foregone income or nutrient losses should be considered excessive, from an economic perspective. If we could compare erosion on securely and insecurely titled land, for example, we might simply assume that the soil on securely held land was being used (i.e., depleted) at an optimal rate. Such information does not exist, for the simple reason that almost no agricultural land in Mali is securely held (excepting rice paddies, where erosion is held to be insignificant).

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