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EROSION, PRODUCTIVITY, AND SUSTAINABLE AGRICULTURE

International Center for Arid and Semiarid Land Studies
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Lubbock, Texas 79409

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EROSION, PRODUCTIVITY, AND SUSTAINABLE AGRICULTURE

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PREFACE

Environmental degradation is a global threat to the sustainability of agriculture. Accelerated soil erosion is a major human-induced cause of environmental degradation. Although accelerated erosion has severely damaged agricultural lands for thousands of years in places such as the Mediterranean region and China, most estimates of the extent and severity of the problem appear to be based on anecdotes rather than on quantitative data.

Sustainable agriculture has long been a primary objective of the projects and programs of the U.S. Agency for International Development. A growing realization that environmental degradation now threatens the survivability of an expanding population has lent increased urgency to efforts to assure the sustainability of agriculture. In response to that urgency, the AID Bureau for Science and Technology Office of Agriculture has undertaken several projects, including the Technology for Soil Moisture Management Project. As part of that project activity, a workshop on Soil Erosion and Sustainable Agriculture in Africa was held at the International Center for Arid and Semiarid Land Studies of Texas Tech University in Lubbock on July 25 and 26, 1988. Participants in the workshop (see list at end of report) came from universities and government agencies in the United States, France, and the United Kingdom.

The objectives of the workshop were to assess the effect of erosion on soil productivity, identify research needs, and evaluate the impact of soil erosion on sustainable agriculture. The working definition for sustainable agriculture was: maintenance of the productivity of the resource base while achieving an economically profitable level of agricultural production.

We thank the workshop participants for their willingness to take time from their busy schedules to provide guidance to the Agency for International Development's continuing efforts to assure that its projects contribute to environmental conservation. The frank and candid discussions demonstrated that knowledgable scientists holding differing opinions can work together to search for workable solutions to difficult problems. Workshop participants recognized the need to take action without waiting for more data and total agreement.

H. E. Dregne, co-chairman
R. E. Meyer, co-chairman

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SUMMARY

Water and wind erosion have severely impaired land productivity in many countries of the world. Erosion is a major threat to the sustainability of agriculture. Water erosion has done the greatest damage to long-term soil productivity; wind erosion is widely acknowledged as a hazard to agricultural sustainability but data to confirm that opinion are scarce. Africa's problems with erosion are particularly significant because agricultural productivity is notably low on that continent.

Maps showing where erosion has reduced long-term soil productivity in Africa are virtually nonexistent at the continental, national, or regional scale. Such maps are needed to enable planners and donor agencies to make wise decisions on the allocation of scarce resources. A limited number of maps depicting the location of eroded lands in small areas have been constructed. They are inadequate to provide information on the severity of the erosion-productivity problem at the national or regional scale. Continental and national erosion hazard maps have been prepared. However, hazard frequently does not equate with actual erosion, and hazard maps tell nothing of the erosion-productivity relation.

In the absence of quantitative data on the impact of erosion on potential soil productivity, recourse can be made to the information experienced people have accumulated over the years. There is a wealth of knowledge among farmers, pastoralists, extension agents, scientists, and conservationists. The problem is to tap these sources in a meaningful way. We propose a "structured informed opinion analysis" system to accomplish that task. The system combines group dynamics and expert system approaches to translate observations into reasonably accurate maps.

Quantitative studies on erosion and the erosion-productivity relation are essential to provide the data required to conduct effective soil conservation programs. We recommend short-term and long-term experiments on sites representative of the major soils and agroecological regions. The tests would be carried out at international agricultural research centers and other research stations, as well as on farmers' fields. Data are especially lacking on the occurrence and impact of wind erosion.

A logical sequence of actions to assess the current status of erosion, to understand the erosion-productivity relation, and to achieve erosion control would be the following:

1. Conduct a rapid analysis of available research data and carry out a structured informed opinion analysis at the national and regional level.
2. Initiate erosion and erosion-productivity short-term and long-term research, including evaluation of the impact of technological packages to increase production, assessment of the on-site and off-site costs of erosion, identification of soil properties important in the erosion-productivity relation, and monitoring erosion and productivity loss by agroecological regions.
3. Develop appropriate soil conservation and yield-increasing practices and devise simple methods to measure erosion losses.
4. Undertake studies to identify constraints and to improve acceptance of erosion control practices by producers of subsistence and commercial crops.

Utilization of the wealth of knowledge that professionals and non-professionals have gained through field experience can enable planners and administrators to implement effective erosion control programs designed to protect the crop-producing capability of a nation.

INTRODUCTION

Agriculture is the engine of economic growth for most developing countries. Agricultural productivity must be sustained and increased if economic growth is to be achieved. Current production practices in many parts of the world are not environmentally sound and are incompatible with the sustainability of agriculture. Water and wind erosion are the principal instruments of the long-lasting soil degradation that poses the most serious threat to environmental stability in croplands. When erosion has reduced the rooting depth and the available water holding capacity of a soil to a critical level, there is no way that natural regeneration can restore productivity in less than hundreds or thousands of years. It is too late to practice conservation when the soil has been eroded away to bedrock.

The African continent has become the focus of donor agency activities in developing countries because it has experienced great difficulty in feeding its people. The continent faces a daunting set of fundamental problems. Three major problems are rapid population growth, enduring economic stagnation and poverty, and declining agricultural productivity. Massive food relief programs must be undertaken every year somewhere in the sub-Saharan region. This is despite the conclusion by the Food and Agriculture Organization (FAO) that the continent has the natural resource potential to support a population of 12. 9 billion at a high level of inputs to agriculture, approximately 34 times the present population (FAO, 1982). Unrealistic though the theoretical population supporting capacity may be, it clearly indicates that the continent can feed much more then its present population if maximum beneficial use were made of its resources.

No reliable data are available on the degree to which erosion has reduced soil productivity in Africa. However, the informed opinion of numerous scientists is that uncontrolled erosion of cultivated land has severely impaired land productivity in countries such as Ethiopia, Lesotho, Zimbabwe, and Tanzania. Water erosion has done the greatest damage; wind erosion is an unmeasured hazard but is widely believed to have an adverse effect on agricultural production in the dry regions (Brown and Wolf, 1984).

The U.S. Agency for International Development cites soil erosion and soil fertility decline as the most serious environmental and economic problems in Africa (AID, 1987). Soil erosion and fertility loss are caused, principally, by extension of cultivation into marginal areas and by inappropriate agricultural practices. In most cases, erosion and fertility decline are closely linked. Globally, the situation is the same, with erosion and overgrazing said to be ruining several million hectares of agricultural land each year (AID, 1988). The seriousness of the erosion problem is undoubted; nevertheless, definitive data on assessment, prediction, and control are missing in most developing countries.

This report is a first attempt to propose techniques for assessing the severity of erosion and its impact on potential soil productivity and the sustainability of agriculture, using Africa as an example.

ASSESSING EROSION AND PRODUCTIVITY

Reliable data on erosion in Africa are restricted to places where experimental plots have been established on research stations. Those are few in number relative to the variety of soils, landscapes, and agroecological zones in Africa. Much less data are available on the effect water and wind erosion have had on the short-term and long-term productivity of the soil (Stocking, 1984). For the purpose of this paper, fertility loss is a short-term effect since it is possible to reverse the loss by applying manure and commercial fertilizers, introducing crop rotations which include legumes, or allowing the land to lie uncultivated for several years. Long-term effects, in our view, are changes in physical and chemical properties that are, for practical purposes, irreversible. The principal changes of importance are soil losses that materially reduce rooting depth, significantly lower the available water holding capacity and the organic matter content, and induce chemical toxicities in crops. It is the long-term effects that are of primary concern when sustainability of agriculture is considered (Papendick et al., 1985). Long-term impacts of erosion may evolve over a short or long time period. Their occurrence is highly site specific.

Erosion hazard maps have been made for the northern half of Africa and for some other countries. Those maps show where soils, landscapes, and climate make the land susceptible to

water and wind erosion. They do not show actual erosion, and there usually is a marked difference between the hazard and the actual erosion condition, due mainly to differences in livestock and human population pressures and in land management practices.

In the absence of good quantitative data on erosion and the relation of erosion to soil productivity, there is urgent need for a simple and rapid procedure for the indirect evaluation of those conditions. Any such practical system will be qualitative in character and subject to the inaccuracies and uncertainties of qualitative analyses. Soil surveys do not ordinarily provide the information needed to determine the occurrence and severity of erosion. Special purpose erosion maps are valuable for showing erosion conditions at the time of the survey. Unfortunately, they are not commonly prepared and they do not indicate the impact erosion has had on soil productivity. Additionally, the absence of field data on erosion means that erosion surveys are, in fact, based largely on the personal opinion of the surveyor and the people the surveyor has consulted.

Conventional soil surveys can be used to assess the vulnerability of soils to erosion under a variety of land use conditions (Manrique, 1988). Vulnerability assessments can be helpful in locating soil areas where particular attention should be paid to the potential for erosion damage to occur. Vulnerability, however, does not equate with occurrence, and it is actual erosion that must be assessed if effective remedial measures are to be taken.

We propose to use the personal opinion of experienced people to meet the need for a simple and rapid method of assessing human-induced erosion and the erosion-productivity relation. There is a wealth of knowledge in Africa, as elsewhere, by local people (farmers, ranchers, extension agents, research scientists, soil conservation professionals, etc.) of the local or regional status of erosion and the impact erosion has had on soil productivity. They represent a largely unused resource that we propose to tap. The procedure for doing so is what we call "structured informed opinion analysis." Its justification is that it represents the best way we know to offset the lack of quantitative data on a problem that requires immediate attention. If we wait to collect data by conventional means, there won't be any soil left to protect. Data obtained with the informed opinion approach can be used to determine exactly where a problem exists and to give a good indication of its magnitude in terms of land damage. That is the first essential step in controlling environmental degradation.

Structured Informed Opinion Analysis

We want to make it clear that the use of informed opinion to make assessments of erosion and the erosion-soil productivity relation can only be justified in the absence of factual data on the phenomena. The information obtained through a structured informed opinion analysis is necessarily of a qualitative character. Accordingly, it must be interpreted and used with caution. Interaction among the knowledgeable persons contributing to the analysis is essential if the observations are to be screened and examined in a manner that will inspire a reasonably adequate level of confidence in the results. Despite the qualitative nature of the information collected, the structured informed opinion analysis is a valuable tool for drawing conclusions in a setting where quantitative data are absent.

The objective of structured informed opinion analysis is to transfer onto maps the qualitative information and mental images knowledgeable people have of erosion and the erosion productivity relation in a specified area. Those maps are to serve as the basis for calculating the areal extent of damaged land, locating the places where conservation practices are needed, and estimating the costs and benefits of remedial measures. Maps are a means of presenting a visual display of the mental picture experts have of the geographic distribution of erosion. Maps can be criticized and changed until a concensus is achieved. Mental images cannot.

The structured informed opinion analysis approach can be used to construct maps of national, regional, district, or local erosion severity. Its utility is greatest, however, at the national, regional, and, perhaps, district level. At the local level, such as in a village, the erosion status of individual tracts of land should already be common knowledge among agriculturalists.

National and regional maps are sources of general information. They are useful to administrators, planners, financial managers, donor agencies, and other non-specialists who want to know where erosion and productivity problems exist and the severity of their present and potential impact. They also can be used to educate the public on the threat posed or the damage done by erosion. One good map is an effective substitute for many long essays, with less

chance for misinterpretation. It is not enough to say, for example, that 15 percent of the cultivated land in Algeria has had its productivity reduced by 25 percent, without producing a map showing where the damage has been and is being done.

The first step in this method of problem analysis is to secure all the ancillary information that is available in the form of soil, vegetation, geology, and topography maps for the local or national region for which an assessment of the erosion-productivity relation is sought. Along with those maps and pertinent reports, whatever data are available should be obtained on weather records, sediment in rivers and streams, and results of experiments that have been conducted. After these pieces of information on natural resources have been analyzed in an integrated fashion, a comprehensive plan should be prepared prior to convening meetings of knowledgeable people. The plan must include a digest of the data analysis and, very importantly, a classification system for the erosion status and the erosion-productivity evaluation. The latter is essential for helping to assure that meeting participants are using the same criteria for assessing the amount and impact of erosion.

Principles of group dynamics and expert system operation should be utilized to obtain a consensus among the meeting participants. The group questioning must be carefully structured to assure participation by all in the discussion, to focus attention on the problem at hand, and to secure a useful outcome. It would be possible to design an appropriate expert system that could be used by individuals to answer the "if-then" questions but group interaction appears to be needed as well as individual responses.

The desired outcome of the deliberations of the group of knowledgeable persons would be a brief document and maps identifying and delimiting the kind of erosion present (sheet, rill, gully), the degree of damage that has occurred, reasons for erosion occurrence, productivity losses, prediction of the cost of continued erosion and productivity loss, appropriate erosion control practices, and costs and benefits of control. The entire exercise could be completed in a few months.

Erosion Data

Many experiments on research station plots have dealt with water erosion in a few agroecological zones of Africa, mainly in the humid and subhumid regions. Thus far, no known published reports have dealt with wind erosion. A few experiments have been initiated in recent years but results have not been published yet. It seems unlikely, but possible, that there is any significant amount of scientific information on wind erosion on agricultural lands hidden in someone's files. Obviously, then, collecting data on wind erosion and its effects needs to be done before it will be possible to assess the severity of the problem with even a modest degree of confidence.

Agroecological Zones

A useful way to organize agricultural and natural resource information is on the basis of agroecological zones. AID has delineated five agroecological zones for the African continent south of the Sahara, plus a sixth for Madagascar and other Indian Ocean islands (AID, 1987). North Africa, from Morocco to Egypt, constitutes a seventh agroecological zone. Each zone has a similar range of rainfed crops, climate, and, generally, soils.

Agroecological zones generated by the FAO Agroecological Zones Project (FAO, 1978) were used to establish the AID zones of Figure 1 (AID, 1987). FAO has published agroecological zone maps for Africa, Southeast Asia, Southwest Asia, and South and Central America. The basic intent of the FAO project was to construct a first approximation of the current and potential use of the developing world's land resources. That information base could then be employed for planning future agricultural developments. Due to the absence of adequate quantitative data on surface and groundwater resources, the project was confined to rainfed agriculture, only.

Each agroecological zone provides the basis for an assessment of the rainfed production potential for the main crops of that zone. For Africa, the crops are millet, sorghum, maize, soybeans, Phaseolus bean, cotton, sweet potato, cassava, and wheat. Length of growing period (rainy period duration) is the first criterion for the agroecological zones. Soil is the second. Within any one zone, there is a similar erosion hazard, production potential, and erosion-productivity relation on similar soils. For example, in the Arid and Semi-Arid Tropics (ASA) zone of Figure 1, water is the limiting plant growth factor, sandy soils are widespread, the dominant crops are sorghum and millet, wind erosion is the dominant erosion hazard, and the long-term productivity loss due to wind erosion seems to have been low throughout the zone.

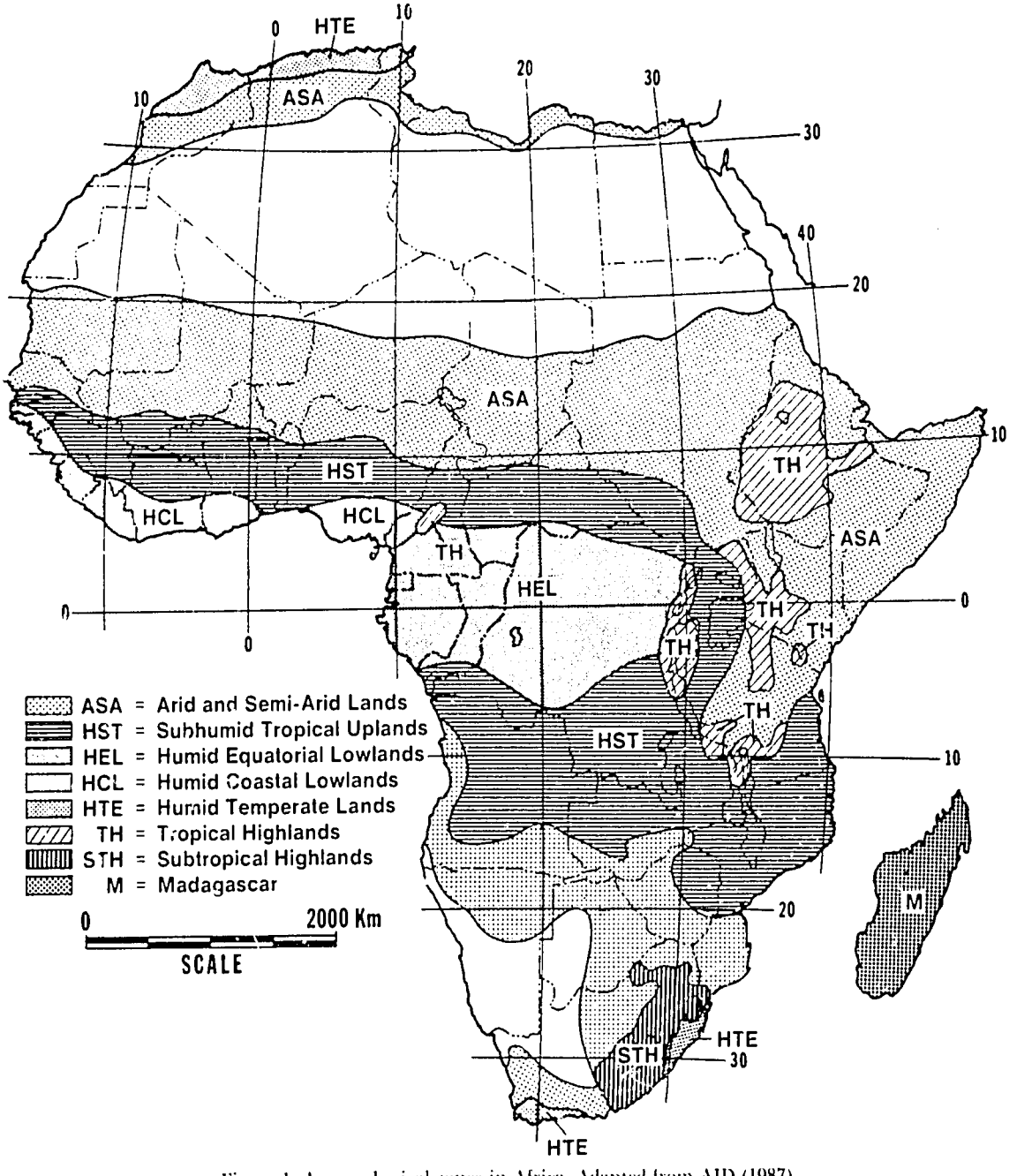

Figure 1. Agroecological zones in Africa. Adapted from AID (1987).

Erosion-Productivity Comparisons

Productivity losses due to accelerated erosion may be short-term or long-term. From the viewpoint of sustainable agriculture, both are important. However, it is the long-term loss that represents a permanent limitation to the crop production potential of the land and is what people mean when they refer to soil erosion as a threat to the survival of the human race.

Figure 2 illustrates three erosion-productivity relations. In each case, no soil conservation measures are practiced, no commercial fertilizers are in use, and erosion is of the rill or sheet type, not gully.

The first graph, Figure 2A, illustrates the short-term reversible loss in productivity associated with rapid erosion of deep soils on moderate slopes in the humid tropics when

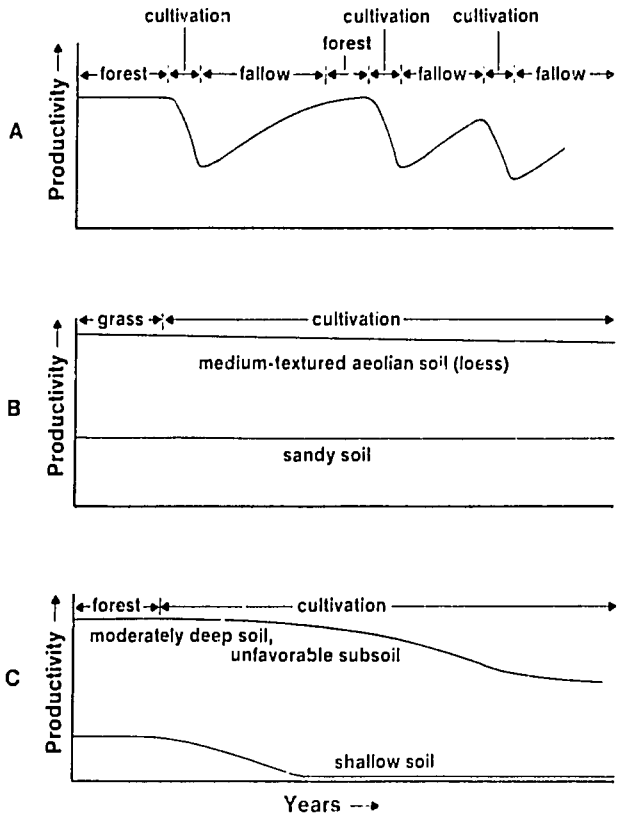

Figure 2. Soil erosion-productivity relations. A) Shifting cultivation, humid tropical forest, deep soil on moderate slope; B) Continuing cultivation of temperate and tropical grasslands, deep uniform soil on moderate slopes; C) Continuing cultivation of temperate forest, moderately deep soil with unfavorable subsoil over bedrock (upper curve) and shallow soil over bedrock (lower curve), moderate to steep slopes, high soil erodibility, high rainfall erosivity.

shifting cultivation is practiced in forested areas using machinery to uproot trees prior to planting the first crop. Erosion is high due to high rainfall erosivities, sloping land, and badly disturbed surface soils. The thin organic layer typical of the humid tropics is rapidly removed, nutrient leaching is high, and the soils are reduced to a low level of productivity in three to four years (Hauck, 1974). The land is then abandoned and allowed to revert to native vegetation. Upon abandonment, restoration of a vegetative cover is rapid, erosion is halted, and fertility and the soil organic layer are re-established in 15 to 25 years. After the forest has been re-established, land will be cultivated again for three or four years, leading once more to soil exhaustion and ultimate abandonment. This sequence of cropping and abandonment is capable of persisting indefinitely with little or no loss in permanent soil productivity. However, if land is cultivated before restoration of the organic matter layer has occurred, yields will suffer (Greenland, 1974). Increased populations have caused a shortening of the fallow period in many shifting cultivation systems, with a consequent lowering of yields in the cropping years. The impact of the shortened fallow period is illustrated in Figure 2A by the lower yield curve during the third cultivation period.

Soils fitting the model in Figure 2A are highly vulnerable to a short-term loss of productivity, primarily due to nutrient problems. Application of fertilizers can sometimes maintain yields at a reasonably good level during the cultivation period if weed and insect damage are minimal (Ofori, 1974). Shifting cultivation systems with short cropping periods and long fallow periods are widespread in the Subhumid Tropical Uplands (HST), Humid Equatorial Lowlands (HEI), and Humid Costal Lowlands (HCL) of Figure 1. They also are extensive in southeast Asia and the Amazon Basin of South America.

The second graph, Figure 2B, presents two examples of situations where even high sheet erosion rates may have little impact on either short-term or long-term productivity. Such conditions exist only where soils are deep and have a fairly uniform profile, with little difference among surface soil, subsoil, and the underlying parent material. Wind-laid soils of medium texture (loessial soils of China, the Soviet Union, and the United States) or deep sandy soils (the Sahel, western India, southern Great Plains) are examples of this condition (Smika, 1987). Loessial soils, especially, are also quite susceptible to gully erosion but the effect of gullies is not considered in Figure 2. Off-site erosion effects are likely to be high, causing river sedimentation, flood damage, and reservoir storage capacity reduction. Whatever loss in productivity may occur is due primarily to reduction in surface organic matter content and the consequent loss of nutrient elements. Such losses can be reversed by increasing the organic matter content and by improving the nutrient status.

The third graph, Figure 2C, represents the worst condition: permanent irreversible soil damage. The destructive combination is a shallow or moderately deep soil over bedrock, moderate to steep slopes, high soil erodibility, and high rainfall erosivity. The upper line in Figure 2C represents a moderately deep soil having an unfavorable subsoil. On that soil, erosion may have only a modest effect until a critical soil depth is reached, after which further erosion

causes a more rapid decrease in productivity, followed by a gradual decline (Onstad et al., 1985). The lower line represents a shallow soil over bedrock. Erosion on that soil can rapidly reduce the rooting zone to the point where the water and nutrient supplying power of the remaining soil will support only severely reduced crop growth, if any, under ordinary conditions. These two kinds of soils are highly vulnerable to long-term productivity loss due to sheet erosion. They are the ones that need early protection against erosion.

Irreversibility of the productivity loss illustrated in Figure 2C is what poses a threat to the ability of the world's population to feed itself. Irreversible soil degradation has occurred in countries around the Mediterranean Sea as well as in the hills of Central and South America, Africa, Asia, Europe, North America, and Australia. The effect has been masked, especially in Europe and the United States, by technological advances, the availability of productive lowlands, and reforestation of the eroded lands. Nevertheless, erosion is irrevocably diminishing the global soil resource. The developed countries can take care of themselves, at least for now, but the poor developing countries facing population increases along with soil degradation have much to be concerned about.

While sheet erosion is the focus of attention in Figure 2, gully erosion is much more destructive since a deep gully cannot be cultivated, even partially. Gullies are spectacular but sheet erosion is the greater global threat. There are no gully erosion models that serve the same purpose that sheet erosion models, such as the Universal Soil Loss Equation, do.

An important matter about which there is little experimental data is that of deciding when land degradation has become so severe that land should be abandoned. Shifting cultivators make that decision regularly, based on experience. In other cases, erosion may become so bad that cropping will be uneconomic even after a rest period of 25 years. Severely eroded hills in the southeastern United States reached that point many decades ago. They provide timber products now and probably will never again be suitable for row crop production (Trimble, 1974).

EROSION CONTROL

There appears to be considerable knowledge of effective erosion control practices in Africa (Greenland and Lal, 1977). Soil conservation techniques have been used successfully in every part of the continent by traditional agriculturalists for decades or even centuries. With the introduction of intensified cash crop agriculture by colonialists, erosion increased and was recognized in the first half of the 20th century as a threat to the sustainability of agriculture. Laws were enacted to force farmers to use recommended erosion control practices. Although many of the practices were effective, adoption by coercion generated resistance. That resistance led to widespread repudiation of conservation as a desirable measure after independence. Recently, the obvious damage erosion has done and is doing has led governments to introduce conservation programs of their own.

The principles of erosion control are well known. Their application, however, is site specific, and much organized and unorganized research has identified effective practices. The key to application of recommended practices is the attitude of the farmers. If they are convinced that the new practices increase yields and do not increase the risk of production, they will accept them. If the required labor to construct terraces and other structures does not bring increased yields immediately or increases the risk, the practices will not be adopted. Long-term benefits are of little interest to people who live from harvest to harvest.

RESEARCH NEEDS

The assessment and prediction method described previously is intended to serve as an emergency measure. Formulating an evaluation of the magnitude and severity of soil erosion and the relation of erosion to potential soil productivity through use of a structured informed opinion analysis is unsatisfying. Data are needed to reduce the uncertainity of the results of an assessment and prediction exercise of this type.

Four kinds of actions are needed, in our opinion, to obtain a better understanding of the wind and water erosion situation in the developing countries of the world. First, there is a need for long-term research experiments to collect data

on runoff, erosion, occurrence and particle composition of dust storms, and crop yields over a long enough period (at least 10 years) to be representative of climatic variations. Obviously, the experiments must be conducted at well-established research stations to help insure continuity. Among the candidate research stations are those operated by the Consultative Group for International Agricultural Research centers such as the International Institute of Tropical Agriculture (IITA), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the International Livestock Center for Africa (ILCA), and the International Center for Agricultural Research in the Dry Areas (ICARDA). Data on the occurrence of dust storms could be collected routinely at stations participating in the World Meteorological Organization (WMO) network. Simple visibility observations are adequate to provide very useful information. Certain stations could be equipped with wind erosion samplers to further expand the information base.

Second, numerous short-term (3-year) research tests on major soils and crops are needed in the various agroecological zones. Those experiments need not be heavily instrumented. Simple collection devices for capturing sediment and dust and for measuring runoff from protected plots at research stations, along with measuring crop yields, would be sufficient. A useful addition to research plots is to estimate the erosion status of farmers' fields by qualitative criteria such as those described in the U.S.D.A. Soil Survey Manual, then collect yields at harvest time from representative parts of fields (Schertz et al., 1985). Where possible, multiple year tests should be run on the same fields since the erosion-productivity relation frequently varies with seasonal wetness or dryness. Interpretation of short-term tests must be done cautiously but the data obtained can be useful in confirming or refuting the validity of estimates. Furthermore, they are low-cost tests that are relatively easy to run when well designed. Short-term erosion-productivity experiments on research stations and in farmers' fields could be the subject of thesis research for M.S. degree candidates at both national and overseas universities. This arrangement would fit nicely into a training system that has students going overseas for their degrees but doing their research at home. Successive students could carry on what would become long-term experiments. Where erosion experiments had been conducted years ago and the site abandoned, students could investigate the changes that had occurred in the intervening years. Such studies could be quite instructive about long-term impacts of erosion.

A third kind of data collection is for water erosion, only. It is the simplest of all and utilizes a well-tested methodology, a device called the Bertrand-Parr Infiltrometer (Bertrand and Parr, 1961). While it was built to measure infiltration in a one-meter square area anywhere in a field, the device can easily be modified to capture sediment in the runoff. The method is useful for making comparisons of relative erosion rates among different soils and land treatments, and for determining the magnitude of interrill erosion. It does not duplicate standard erosion plot data because of the small distance of surface water flow. It requires a vehicle capable of carrying a relatively small amount of water sufficient to saturate the surface of the one square meter of soil. Numerous tests can be conducted in a few days.

Before any of the field experiments are undertaken, fairly intensive local soil mapping should be done to assure that the sites are representative of larger areas and that the soils have been characterized in sufficient detail to enable them to be fitted into a classification system.

Wind erosion field tests present a more difficult problem than do water erosion tests. The principal reason is that the tools to quantify wind erosion were not even available until after 1983. In recent years, development of measuring devices has progressed to the point that it is now possible to evaluate the magnitude and extent of the impact of wind erosion on soils, crops, and the environment. Obviously, it will be many years before there will be a significant amount of experimental data available from tests conducted under different cropping and environmental conditions. In the meantime, quantitative measurements of the number, frequency, intensity, and duration of dust storms and analysis of the collected particles to identify the source and composition of the eroded material would be valuable in evaluating the significance of the problem.

Fourth, water and wind erosion models offer great promise as means of providing reasonably accurate estimates of soil erosion under a wide range of climate, soil, crop, and topographic differences. In the long run, reliable models are absolutely essential to handle the many erosion and productivity variables at a tolerable cost. Physically based models presently under develop-

ment, such as the U.S. Department of Agriculture's Water Erosion Prediction Project (WEPP) and the Wind Erosion Prediction Model (WEPM), should be a considerable improvement over the Universal Soil Loss Equation (USLE) and the Wind Erosion Equation (WEQ). The latter models have worked well in the temperate zones but there have been difficulties in employing them in the tropics where rainfall erosivities, crops, and soils differ markedly. The same handicap faces the SLEMSA (Soil Loss Estimation and Monitoring in Southern Africa) model developed in Zimbabwe. Despite the minimum amount of testing of SLEMSA, USLE, and WEQ in the tropics, they may be useful to provide first approximations of erosion severity. The USLE can be quite useful in West Africa (Roose, 1976), and elsewhere if its factors are modified to reflect local cropping conditions. No other models have been shown to be better. The modelling effort should be closely associated with the long-term data collection experiments mentioned previously.

For estimating productivity changes due to erosion, the best available model may be the Erosion-Productivity Index Calculator (EPIC) (Williams and Renard, 1985). EPIC is routinely used in the periodic natural resource inventories of the U.S. Department of Agriculture. While the data requirements for running the model in its full configuration are more than most developing countries can supply, simplifications have been devised recently that may give useful estimations of the erosion-productivity relation in places where the data base is more limited.

EROSION RESEARCH PRIORITIES

Sustainable agriculture is impossible if uncontrolled erosion is allowed to destroy the soil resource upon which all agriculture depends. As it is now, an abysmally small amount of data has been collected that directly relates to soil erosion and the associated reduction in potential soil productivity. This is true of developed as well as developing countries but the situation is much more acute in developing countries where population pressures, poverty, and low agricultural production present an immediate threat. Furthermore, what data are available are usually hidden away in some long-forgotten file.

In view of the hazard soil erosion poses, we propose the following research priorities:

1. Collate, analyze, synthesize, and interpret available research information on erosion and soil productivity.
2. Compile best available estimates of the extent and severity of soil erosion and soil productivity loss.
3. Initiate long-term experiments to assess erosion-productivity relations and to evaluate yield-increasing technological packages for their productivity, sustainability, and risks of environmental pollution at different levels of inputs and on sites representative of major soils and ecological regions.
4. Assess economic cost of soil erosion, on-site and off-site.
5. Establish test plots to monitor soil erosion and productivity loss on sites representative of major soils and ecological regions.
6. Conduct research on relation of soil loss to changes in soil properties affecting soil productivity in the semi-arid and humid tropics.
7. Develop soil conservation and yield-increasing practices suitable for erosion control in the semi-arid and humid tropics.
8. Develop low-cost methods for measuring soil erosion.

An important area of sociological research that needs study is farmers' perceptions of erosion and its impacts. For control to be achieved, farmers must be convinced that there are benefits that will accrue to them. If no such benefits are apparent, governments will have to induce the farmers, through some kind of subsidy program, to carry out the conservation practices.

OFF-SITE COSTS

There appears to be little information on the off-site costs of erosion in Africa. It seems likely that the same off-site damages occurring elsewhere, such as water pollution, air pollution, loss of reservoir capacity, increased flooding, and flood plain sedimentation, are occurring in Africa. Off-site costs of both water and wind erosion are several times greater than on-site costs in the United States. The situation may or may not be similar in other countries.

The significance of high off-site costs, insofar as erosion control measures are concerned, lies in the importance of reducing erosion wherever it is excessive, not just where erosion adversely affects

crop production. Farmers usually will have little reason to reduce off-site damages unless they themselves receive some direct economic benefit. Governments would need to bring about control through the use of subsidies or the imposition of penalties.

SUSTAINABLE AGRICULTURE

Many definitions of sustainable agriculture have been proposed. No one definition satisfies everyone but there probably is fair agreement that sustainability must insure that food production can be continued indefinitely without destroying the natural resource or economic base which supports it. For that to occur, each acre of agricultural land must be used within its capabilities and treated in accordance with its need for protection and improvement (Troeh et al., 1980).

Globally, soil erosion unquestionably is the dominant threat to sustainable agriculture. No miracle of plant breeding can eliminate the need for adequate available water and nutrient holding capacity in soils used for rainfed cropping. Once the rooting depth of a soil has been reduced below a critical level, the long-term productivity will be impaired for the foreseeable future.

Achieving sustainable agriculture in developing countries experiencing significant erosion damages can be difficult. Rarely, if ever, would financial and human resources be immediately available to undertake a comprehensive soil conservation program. Choices must be made. As Figure 2 illustrates, continued erosion on soils of low initial productivity would be expected to reduce crop yields less than continued erosion on soils of medium or high productivity. However, it also is likely that the low productivity soils are farmed by the poorest members of the rural society, with the least resources available to control erosion. On the other hand, the highly productive soils probably are farmed by the wealthier segment of the population, with the best ability to institute conservation practices. Equity calls for helping the poor but efficiency calls for protecting the good lands.

Another potential dilemma is whether public funds should be expended on protecting the highly productive soils from possible future erosion as opposed to protecting already-eroded lands from further degradation. The first option represents the most efficient use of scarce funds but the second is more environmentally desirable.

DATA UTILIZATION

Much can be done expeditiously and well to assess and map the occurrence and severity of soil erosion and its impact on soil productivity, for regions and nations. There is a pronounced absence of quantitative data on the status of erosion and the erosion-productivity relation. However, there is a wealth of qualitative knowledge about the subject possessed by professionals and laymen having field experience. The proposed structured informed opinion analysis represents a technique that utilizes the best available information to construct erosion and erosion-productivity maps rapidly. Planners and managers need that information if they are to make intelligent decisions on the allocation of financial and human resources. Waiting decades to acquire definitive quantitative data on the erosion problem is unacceptable in countries facing serious land degradation problems. In most cases, it is not necessary to wait for more quantitative data in order to initiate an effective conservation program, if such a program is needed.

The informed opinion analysis would identify several categories of erosion. Among these categories would be the following: 1) erosion rates tolerable, 2) erosion high but productivity loss low, 3) erosion causing reversible productivity loss, 4) erosion causing irreversible productivity loss, and 5) erosion damage low but threat to productive lands high if erosion continues or increases. Maps would show where the different categories of erosion occurred. They would allow conservation measures to be targeted to places where the cost/benefit ratio was most favorable.

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