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Soil erosion effects on soil productivity: A research perspective

By the National Soil Erosion-Soil Productivity Research Planning Committee, Science and Education Administration—Agricultural Research

ACCURATE estimates of future soil productivity are essential to make agricultural policy decisions and to plan the use of land from the field scale to the national level. Soil productivity is the capacity of a soil, in its normal environment, to produce a particular plant or sequence of plants under a specified management system (*96*). Because of the emphasis on a soil's capacity to produce crops, productivity should be expressed in terms of yields.

Soil erosion depletes soil productivity, but the relationship between erosion and productivity is not well defined (*63, 67, 80, 83, 99, 100*). Until the relationship is adequately developed, selecting management strategies to maximize long-term crop production will be impossible. Poor decisions can easily result in serious damage to soil resources; productivity may approach zero in many severely eroded areas of the United States (*10, 11, 12, 15, 43, 52, 53, 60, 89, 117*). Poor decisions can also result in under use of soil resources and loss of income to the producer and food and fiber supply to the consumer.

Although limited research has been devoted to the soil erosion-soil productivity problem specifically, considerable effort has gone into most of the important processes involved. However, the necessary components (hydrology, erosion-sedimentation, nutrient cycling, crop growth, tillage, animal uptake, etc.) have not been linked in a model appropriate for studying the erosion-productivity problem.

The RCA imperative

In response to Public Law 95-192, the Soil and Water Resources Conservation Act of 1977 (RCA), the secretary of agriculture was requested to make an appraisal of soil, water, and related resources and their conservation and to make informed, long-range policy decisions regarding the use and protection of these resources. With development of plans to implement RCA, it became obvious that there existed no reliable method for estimating the cost of erosion or the benefits from erosion research and control.

In an effort to overcome this deficiency, two U.S. Department of Agriculture (USDA) scientists, Hagen and Dyke (*48*), developed an empirical crop yield-soil loss relationship for use in the RCA appraisal process. The crop yield-soil loss regression equations provided information for a linear programming model used to determine the best national management policies. The effort by Hagen and Dyke was particularly significant because it was the first attempt to develop a nationally applicable crop yield-soil loss relationship. In many areas of the country, however, their results differed widely from independent experimental observations not used in developing the equations (*1, 2, 5, 8, 10, 16, 17, 19, 24, 27, 28, 32, 33, 34, 35, 36, 37, 38, 44, 45, 54, 57, 60, 61, 62, 67, 70, 76, 81, 87, 101, 104, 112*).

USDA held a workshop in February 1980 to discuss ways of improving the crop yield-soil loss relationship. Economics and Statistics Service (ESS) scientists, who developed the empirical relationship, described their approach to representatives of the Soil Conservation Service (SCS) and the Science and Education Administration—Agricultural Research (SEA-AR). The workshop provided an excellent audience to critique the ESS crop yield-soil loss prediction method. Also, research results, current research on the problem, and future research approaches were discussed.

It became apparent during these discussions that the erosion-productivity problem deserved special attention. Thus, in an effort to develop a suitable soil erosion-productivity relationship, the National Soil

The National Soil Erosion-Soil Productivity Research Planning Committee was created within the U.S. Department of Agriculture's Science and Education Administration—Agricultural Research to assess past, present, and future research on the relationship between soil erosion and soil productivity. J. R. Williams, a hydraulic engineer at the Grassland, Soil and Water Research Laboratory, P.O. Box 748, Temple, Texas 76501, served as chairman of the committee. Other committee members included SEA-AR scientists R. R. Allmaras, K. G. Renard, Leon Lyles, W. C. Moldenhauer, G. W. Langdale, L. D. Meyer, and W. J. Rawls. Gerald Darby and Raymond Daniels represented USDA's Soil Conservation Service and Richard Magleby represented USDA's Economics and Statistics Service.

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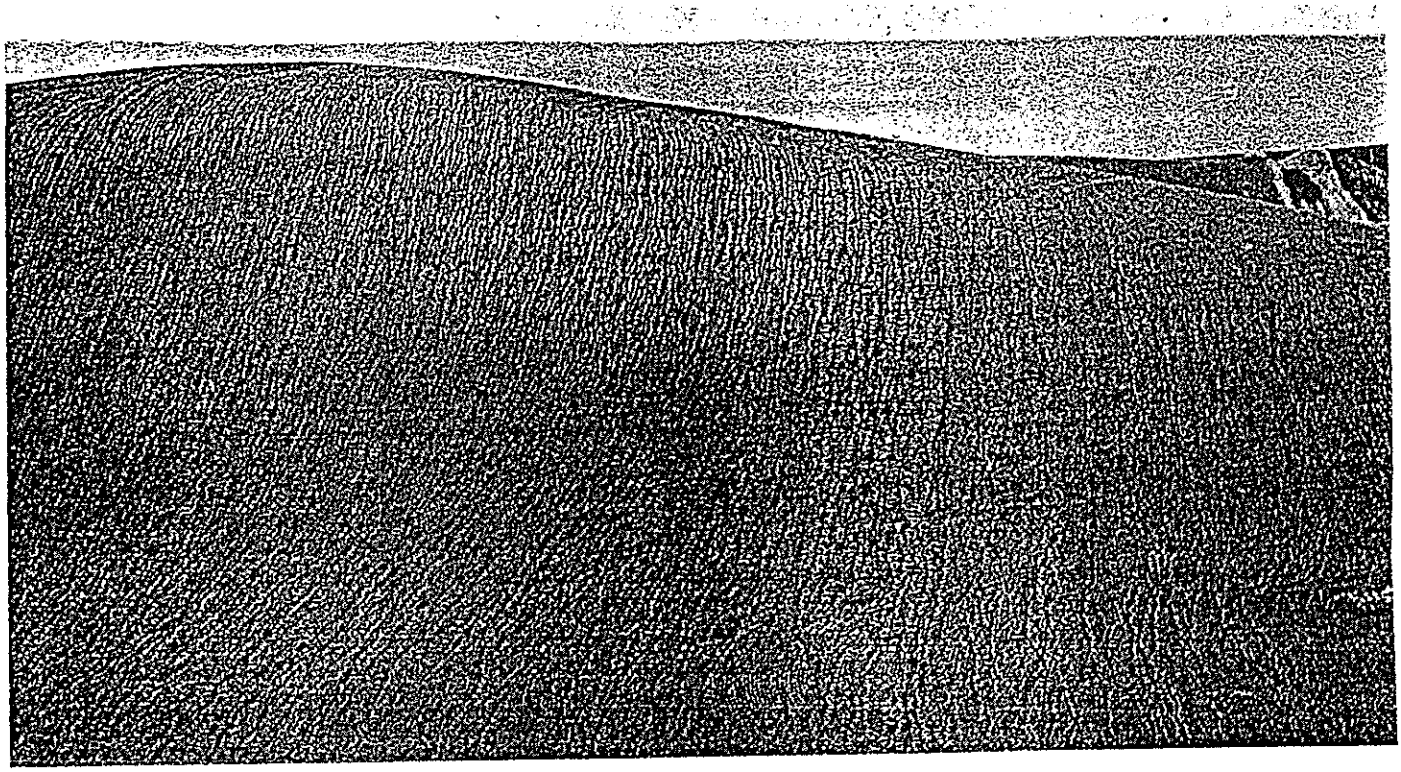


rosion-Soil Productivity Research Planning Committee was appointed. This committee was given three objectives:

1. To determine what is known about the problem by (a) defining it, (b) identifying research accomplishments, and (c) identifying current research efforts.
2. To determine what additional knowledge is needed.
3. To develop a research approach for solving the problem.

The erosion-productivity problem

One of the most dangerous characteristics of the erosion-productivity problem is its difficulty of detection (*63*). Erosion reduces productivity so slowly that the reduction may not be recognized until land is no longer economically suitable for growing crops. Furthermore, improved technology often masks the reduction in productivity (*60*). Some eroded soils, for example, respond well to heavy fertilizer applications (*60, 63*).

The difficulty of detecting productivity losses is compounded by the nonlinear nature of the erosion process. Erosion generally increases future runoff because of reduced infiltration. Increased runoff reduces available soil water, thus plant growth. Of course, less plant growth means less residue. Less vegetation and residue provide less cover, which increases erosion. Because water erosion strongly relates to runoff (*113*), increased runoff also leads to increased erosion. The process thus advances exponentially, and reversing it may quickly become economically impossible if it is not detected and controlled properly.

Because of the nonlinear advance of erosion, subsoils are being exposed at an accelerated rate in many places. Prior to intensive cropping, native grasses and trees protected most topsoil. Once cultivation began, erosion exposed some subsoils within a few years. Since that exposure, the erosion process has accelerated rapidly.

Another cause of accelerated exposure is that exposed subsoils may increase erosion on adjacent areas of a field. When a clay or sodium-saturated subsoil is exposed, infiltration declines, runoff increases, and erosion accelerates on adjacent, down-slope soils. Also, ridges or knolls of exposed calcium carbonate provide readily movable soil material for wind erosion on adjacent soils. In both cases the lack of sufficient crop residue compounds the problem.

Still another characteristic of the erosion-productivity problem is the difficulty of restoring the productivity of severely eroded soils. Restoration is generally difficult and costly because subsoil conditions often inhibit crop growth (*8, 33, 34, 35, 36, 54, 64, 82, 86, 105*). These conditions include poor aeration, low organic matter, lack of exchangeable or soluble nutrients and calcium carbonate, high soluble aluminum, gravel, and high density (strength). Although productivity can be partly restored by adding organic material and fertilizer, such additions may not be economical. For example, eroded rangeland is particularly difficult to restore because fertilization usually is not economical in low-rainfall areas (*86*).

Ways erosion reduces productivity

Erosion reduces productivity first and foremost through loss of plant-available soil water capacity. Lower soil water capacity subjects crops to more frequent and severe water stress. Plant-available soil water may be reduced by changing the water-holding characteristics of the root zone or by reducing the depth of the root zone. Erosion reduces root-zone depth if subsoils are toxic to roots or have high strength or poor aeration that retards root growth. The water-holding characteristics of the root zone are almost always changed when topsoil is removed because topsoil usually has a higher plant-available water capacity than subsoil.

Erosion also reduces productivity by contributing to plant-nutrient losses. Eroded soil particles carry attached nutrients from fields into streams and lakes. Because subsoils generally contain fewer plant nutrients than topsoils, additional fertilizer is needed to maintain crop production. Although fertilizer can partially compensate for low crop yields on exposed subsoils, production costs are increased (*5, 8, 13, 17, 19, 30, 32, 33, 34, 36, 39, 46, 51, 54,*

56, 65, 74, 76, 78, 81, 82, 94, 106, 116). The problem is further compounded if the subsoil contains more clay than the topsoil—a common occurrence. Clay tends to transform applied phosphorus quickly into forms not readily available to plants.

A third way erosion reduces productivity is by degrading soil structure. Degradation of soil structure increases soil erodibility, surface sealing, and crusting and leads to poorer seedbeds. Surface sealing and crusting reduce seedling emergence and infiltration. Reduced infiltration provides less opportunity for soil water storage.

Erosion also reduces productivity through nonuniform removal of soil within a field. Erosion does not occur uniformly across a field mainly because of the runoff flow network and nonuniform topography. Selecting a management strategy to maximize production is nearly impossible in fields with various degrees of erosion because fields are usually farmed as units. When fields are farmed as units, fertilizer is normally applied uniformly over the field. If erosion is nonuniform, the application rate is more appropriate for some areas than others (optimal production is impossible for all areas).

The effect on herbicide use is similar. Because herbicides interact with soils, their performance varies with soil organic matter content, pH, and cation exchange capacity. In a nonuniformly eroded field one rate of herbicide application may kill weeds and damage the crop in one part of the field but not effectively control weeds in another part of the field.

Nonuniform erosion also affects the timing of farming operations. Proper timing, especially in planting, has an important impact on productivity. Frequently, erosion-exposed clay subsoils are too wet when the rest of the field is suitable for farming operations. The farmer must either avoid these clay areas or wait until they are dry enough to permit tillage. Nonuniform erosion also affects tillage effectiveness and causes inconsistent seedbeds that produce poor stands and variable emergence (*37, 38*).

Energy requirements are also greater for nonuniformly eroded fields. Tilling a subsoil usually requires more power than tilling a topsoil. Additional energy is also needed for filling and smoothing gullies. If gullies are neglected, row lengths are shortened, reducing farming efficiency.

Although there are probably many other ways that erosion reduces productivity, these four are the most important. Evidence of productivity loss caused by erosion exists throughout the United States. Many once-productive fields have not been cultivated for years because severe erosion made cropping unprofitable. Proof of extensive erosion losses since cultivation began is exhibited by rapid increases in floodplain elevations from sedimentation (*88*).

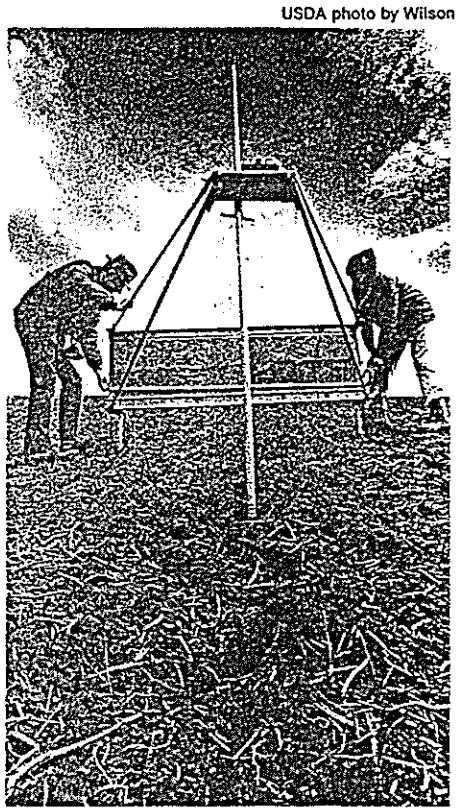
Some research accomplishments

Research to determine the effects of soil erosion on crop production is limited. There are two important reasons why.

First, such experiments are costly and time-consuming. Years of data are needed to evaluate the effects of the generally slow process. Also, results can be difficult to interpret. Other variables may mask erosion-productivity relationships.

Second, because crop production has been adequate in the past, there has been little incentive for investment in this type of research. A few recent field experiments demonstrate that erosion can drastically reduce crop yields (*8, 10, 16, 43, 45, 60, 62, 67, 68, 70, 71, 85, 91, 92, 95, 106*). However, climatic characteristics vary widely throughout the United States and have important effects on both soil erosion and crop production. Therefore, research conducted on one physiographic land resource area represents a relatively small fraction of the country's land area.

USDA photo by Wilson



Rill dimensions measured with this "rill meter" will enable these agricultural scientists to calculate the soil lost as a result of erosion on this Palouse cropland in eastern Washington. More than a fourth of the nation's 413 million cropland acres is eroding at a rate that lowers soil productivity.

Available research is also limited temporally as well as spatially. Most field studies last only a few years. Such studies, unfortunately, provide information influenced by climatic variability that usually is not representative of long-term climatic variability. However, it would be difficult to develop a meaningful erosion-productivity relationship even using long-term data for a physiographic region because of the masking effects of other inputs (more productive crop varieties, increased fertilizer and pesticide application rates, improved management skills, and improved materials and equipment).

Effects of water erosion

Research began in the early 1930s at erosion experiment stations to investigate the effects of erosion on crop production, runoff, and soil loss. This research was authorized by the 1928 Buchanan Amendment to the Agricultural Appropriaton Bill. The erosion experiment stations were located on the most erosive land in the nation (*14, 26, 31, 50, 55, 58, 75, 84, 93*).

Control plots were established and some plots were desurfaced (topsoil removed) for comparison with plots under normal conditions. Although little or no fertilizer was applied during most of the experiments, results of the studies provided an indication of erosion's effects on productivity.

In the Rolling Red Plains near Guthrie, Oklahoma, experiments with continuous cotton revealed that the 11-year average runoff from desurfaced plots with a 7.7 percent slope was about twice that from control plots with the same slope (*31*). Erosion on the artificially desurfaced plots averaged about 50 percent more than on the control plots for the 11-year period, and cotton production declined 40 percent over the period. Results from naturally eroding plots showed the same general trend as the artificially desurfaced areas.

Continuous-corn yield on a desurfaced plot in the Missouri Valley loess region (Clarinda, Iowa) averaged 20 percent of that on a check plot during a 4-year period (*75*). Runoff and eroson were considerably greater on the desurfaced plot during the same period.

During a 9-year period at Zanesville, Ohio, 15 centimeters (6 inches) of Muskingum loam eroded from a plot in continuous corn on a 12 percent slope (*14*). Muskingum loam has a channery loam subsoil with bedrock at about 90 centimeters (36

inches). Soil organic matter content fell from 2 to 0.5 percent. Although corn yields varied from year to year—maximum yield was 3,765 kilograms per hectare (60 bushels per acre) and minimum yield was 100 kilogram per hectare (2 bushels per acre), the trend declined uniformly from about 2,500 kilograms per hectare (40 bushels per acre) to 100 kilograms per hectare. An average of 1.9 centimeters (0.75 inch) of soil was lost each year.

At Bethany, Missouri, the 10-year average corn yield on a desurfaced plot of Shelby silt loam was 47 percent of that on a control plot (*93*). Shelby silt loam has a clay loam subsoil. Runoff and erosion were unexplainably greater on the control plot than on the desurfaced plot.

In North Carolina seed cotton yields on desurfaced plots of Cecil sandy clay loam with a 10 percent slope averaged 47 percent of the yield of that on control plots (*26*). Runoff and soil loss were about the same on the control and desurfaced plots.

Cotton yield on a desurfaced plot of sandy clay soil in East Texas averaged 32 percent of that on a control plot over a 10-year period (*84*). Runoff was about 50 percent greater and soil loss was two to three times greater on the desurfaced plot for the same period. Soil loss on the 8.75 percent slope averaged 3 to 8 millimeters (.1-.3 inch) per year for 10 years with average annual rainfall of 103.3 centimeters.

Field trials in Minnesota and Wisconsin showed that grain yields on severely eroded soils in Minnesota were about two-thirds of the yields on slightly eroded soils (*50*). In Wisconsin yields on severely eroded land were about 75 percent of those on slightly eroded land.

At Temple, Texas, crop production in a cotton-corn-oats rotation on a desurfaced plot of Austin clay with a 4 percent slope averaged about one-third of that on plots with normal soil profiles (*55*). Austin clay has a clay surface and subsoil. Runoff on the desurfaced plots was 2.5 times that on the normal soil plot, and soil loss was 1.5 times greater on the desurfaced plot for an 11-year period.

Winter wheat-fallow rotations were tested on Palouse soils with a 30 percent slope (*58*). Wheat yield on desurfaced plots was 40 percent of that on check plots. Runoff was 2.5 times greater on the desurfaced plots, and soil loss was 9 times greater during the 10-year period.

In New Mexico cover density on rangeland was found to be a function of erosion (*25*). Under normal erosion, a 35 percent cover density was comprised of 28 percent grass, 2 percent forbs, and 5 percent shrubs (3 percent slope). For advanced erosion, "beginning of rapid destruction" [1.9 centimeters(0.75 inch) of soil loss], cover density was 25 percent (20 percent grass, 3 percent forbs, and 2 percent shrubs). With excessive erosion [7.6 centimeters (3.0 inches) of soil loss] on slopes of 3 to 35 percent, a 13 percent cover density was observed (3 percent grass, 2 percent forbs, and 8 percent shrubs).

Soil Conservation Service photo by Peden

No-till planting of corn in corn residue was among the many forms of conservation tillage that were used last year on about 60 million cropland acres nationwide.

Baver (*9*) and Bennett (*12*) discussed the potential yield reductions caused by soil erosion on the basis of research prior to 1950. Nationally, productivity of eroded soils related closely to the environment and nature of the soil profile. Most early water erosion research, however, was conducted at low crop production levels (*1, 4, 6, 7, 14, 24, 26, 29, 31, 42, 46, 50, 51, 55, 58, 64, 66, 74, 75, 76, 77, 90, 92, 93, 97, 105, 109*). Although soil erosion is always costly to producers, it is difficult to extrapolate low-level production technologies to the current high levels of production (*63*).

The most important benefit of the early erosion research was the development and application of soil conservation practices. With proper management, the conservation systems effectively controlled erosion and thus maintained soil productivity.

Maintaining soil productivity today is probably the most difficult on fragile rangeland in arid regions because soil tilth and organic matter are difficult to restore without adequate water. These conditions are nearly irreversible (*70*). Other potentially irreversible conditions, mainly caused by gully erosion, exist on soils derived from loess in the Palouse area of the Pacific Northwest (*2, 57, 58, 60*), the Mississippi Valley of western Tennessee and Mississippi, and bluff sites of western Iowa and surrounding areas (*10, 16, 63, 89, 100*).

In the humid eastern United States grain yields decline 30 to 40 percent and forage yields 20 to 30 percent when the A horizon is eroded away (*1, 8, 16, 43, 62, 63, 64*). Limited research suggests that yields can be restored if abundant water and mulch supplies are accompanied by intensive fertilization (*8, 42, 61, 63, 78*).

Phosphorus apparently is the most deficient plant nutrient in eroded soils (*63*). Numerous soil fertility investigations on land with the topsoil removed by land forming revealed similar phosphorus deficiencies (*9, 17, 18, 19, 32, 33, 34, 35, 36, 37, 38, 39, 54, 82, 85, 104*). These studies are useful in planning research for restoring crop production on eroded lands. A few studies reported that only intensive nitrogen and phosphorus fertilization was necessary to restore crop production (*19, 37, 38, 78, 87*). In the Southeast productivity is more difficult to restore because of chemical and physical conditions associated with acid subsoils (*9, 81, 104*).

Research showing that land forming may reduce crop yields suggests indirectly that erosion will lower productivity, although the time scale of removal is different—instantaneous for mechanical soil re-

moval and slow for erosion (*18, 34, 49, 54, 87, 112*). Also, results vary with soil profile characteristics. In rare cases a subsoil may be a highly productive medium because it is composed of buried topsoil.

Effects of wind erosion

Although much as been written about wind erosion, especially during and after the drought of the 1930s (*110*), these writings generally have dealt with the mechanics of the erosion process, identification of onsite and offsite damages due to erosion, and the principles and practices for control. Only gross quantitative estimates are currently possible for assessing the effects of wind erosion on soil productivity (*67, 68*). Loss of topsoil, plant nutrients, and organic matter as well as changes in soil texture caused by wind erosion are among the factors that by implication lower productivity (*21, 22, 29, 30*).

After surveying wind erosion damage in a 20-county area [6.6 million hectares (16.3 million acres)] of southwestern Kansas, southeastern Colorado, and the Panhandles of Oklahoma and Texas in 1935, Joel (*59*) recommended that 1.7 million hectares (4.2 million acres) be returned to permanent native vegetation. That represented 52 percent of the cultivated and idle land (formerly cultivated) in the survey area. Such a large reduction in cultivation would seriously lower grain production in the area.

Several studies have related yields of certain crops to soil thickness for a limited range of soils, generally fine-textured soils. Lyles (*67, 68*) and Pimentel and associates (*83*) have summarized this work. Rough estimates of yield reductions per millimeter of topsoil loss might be 10 kilogram per hectare (.2 bushel per acre) for corn and 8 kilograms per hectare (.1 bushel per acre) for wheat, soybeans, grain sorghum, and oats. However, the data are too sparse to extend across soils, climate, and type of erosion (wind or water).

Mathematical modeling

Mathematical modeling, another research approach, has had limited, direct application to the problem. Erosion models have been developed for designing erosion control systems (*40, 41, 69, 72, 73, 117, 118*), predicting sediment yield for reservoir design (*79, 86, 113*), predicting sediment transport (*114, 119*), and simulating water quality (*98, 103, 115*). Also, soil characteristics have been used to compute soil productivity ratings (*3, 47, 102*). Previously, normal yields and production practices were given for various soil types in Mississippi (*107, 108*). However, erosion models have not been linked with crop growth models to form the necessary structure to study the erosion-productivity problem. The immediate need for a relationship between erosion and productivity (1980 RCA appraisal) led to the development of the ESS yield-soil loss regression equations (*48*).

Current research efforts

Although the research resources directed specifically to the soil erosion-soil productivity problem are limited, considerable work is underway on most of the important processes involved. SEA-AR research relative to the problem includes the following: (a) tillage practices for improving soil properties and crop growth; (b) management and use of precipitation and solar energy for crop production; (c) use, management, and conservation of soil fertility for increased production and nutritional quality of plants and animals; (d) pollution prevention and improvement of soil, water, and air quality; (e) control of water erosion, wind erosion, and sedimentaton; and (f) conservation and management of agricultural water resources.

In addition, two national modeling teams are working on closely related problems—crop growth and nonpoint-source pollution. The nonpoint-source pollution team has developed a field-scale chemical transport model called CREAMS (*111*)—Chemicals, Runoff, and Erosion from Agricultural Management Systems. CREAMS is operational, but testing and refinement continue.

The crop-growth team is developing plant cycle models with particular emphasis on economically important crops, such as cotton, wheat, corn, and soybeans.

Other models that have linked some of the components necessary in simulating the erosion-productivity process are being developed at several SEA-AR locations. In St. Paul, Minnesota, several important components are being linked to form a model for use in agricultural production research. This model is unique because it includes a tillage component based on extensive tillage research in the Midwest. In Oxford, Mississippi, hydrologic and erosion-sedimentation models are being linked to a cotton growth model for use in studying hydrologic and erosion-sedimentation processes. In Temple, Texas, hydrology, erosion-sedimentation, nutrient cycling, crop growth, and economic models are being linked to form management models that will be used for research purposes also. And finally, in Boise, Idaho, a team is being formed to develop rangeland ecosystem models.

Current field research to evaluate the effects of soil erosion on productivity is limited to a few locations in the United States. At the University of Tennessee, soybean yields are being studied on several soils with different degrees of erosion. Preliminary results indicate that severe erosion significantly reduces soybean yields on fragipan soils (Grenada) and soils over sandy substrata (Lexington). Yield reductions were less on Memphis soils than on eroded Grenada soils. The yield reduction was greatest during the year when moisture was deficient.

Studies are underway at the University of Kentucky to determine the effects of erosion on corn yields, soil properties, and the need for increased lime and fertilizer for different cultural practices. Results indicate that average annual corn yields with no-till farming are considerably higher on uneroded land than on eroded land.

In Georgia, SEA-AR researchers are studying the effect of conservation tillage on erosion and the use of conservation tillage on eroded Piedmont soils. Their goal is to obtain economical crop yields with minimal erosion.

Several studies are being conducted to determine the effects of erosion on soil characteristics that influence crop growth. Work at the University of Idaho is looking at how topsoil thickness affects infiltration, plant-available water, nutrient status, and plant response. At Big Spring, Texas, SEA-AR researchers are measuring changes in physical and chemical soil properties that are affected by wind and water erosion. They are also attempting to relate the soil properties to crop yields.

The STEEP (Solutions to Environmental and Economic Problems) program in the Pacific Northwest deserves special note. This research is focusing on the region's critical erosion problems, using an interdisciplinary approach to problem solving.

Each county soil survey published in recent years by SCS in cooperation with the state agricultural experiment stations shows the expected yields of major crops for each major erosion class and slope of the soils. These yield averages are based on field observations. They often include yield measurements from fields with different topsoil depths. Examples of field yield evaluations are SCS studies in New Mexico, on dryland grain sorghum with different degrees of wind erosion, and in Alabama, relating yield to A horizon thickness. The published SCS yield evaluations

are regularly updated to show the current expected yields of major crops under a high level of management.

SCS periodically reviews the soil loss tolerance limits (T-values) for all major soils also. There is essentially no research base to support T-values; they were established and are revised on the basis of collective judgments by soil scientists. Recommended T-values are based on several criteria, one of the most important of which is sustained productivity. Productivity is not always the active constraint, however.

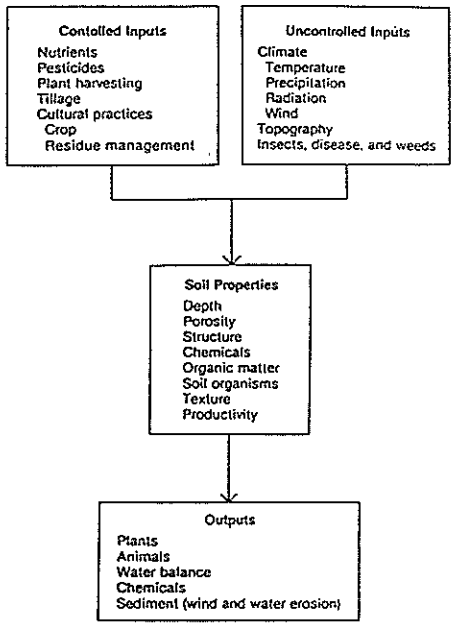
Research is also being conducted in an attempt to separate the effects of improved technology from those of erosion on productivity. An SCS-SEA case study in Whitman County, Washington, is looking at the extent to which improved modern production technology masks soil erosion's effects on productivity. SEA-AR research at Mandan, North Dakota, involves an evaluation of the efficiency of fertilizer and cropping practices in restoring the productivity of subsoils exposed by erosion. The Tennessee Valley Authority is developing methods to recover crop yields on eroded soils in west Tennessee and northern Mississippi.

Various agencies, particularly state agricultural experiment stations and the U.S. Forest Service, are conducting research to determine uses for severely eroded cropland that is no longer suitable for annual cropping. Goals are to find uses that would at least stabilize the remaining soil and, if possible, produce some economic return. Some of this land remains suitable for pasture or hardwood production, but most has been so abused that it is suitable only for pine forestry.

Results throughout the United States show that the productivity of such worn-out land relates directly to the depth of topsoil that remains (*20, 23*). Research is continuing to develop better methods for selecting the most suitable and economical species of vegetation for site-specific conditions.

Considerable research is being conducted to determine the effects of land grading (cuts and fills) on crop production. When surface soil is removed for land forming, the result may be similar to that from erosion, although the abrupt loss generally affects immediate productivity more than a gradual erosion loss.

Much current research is directed toward reducing nonpoint-source pollution and cleaning rural waters. Although this work is mainly concerned with downstream effects of runoff, sediment, plant nutrients, and pesticides, it considers several of the processes involved in erosion-productivity research. For example, runoff



Factors considered in building a mathematical model to quantify the effects of erosion on soil productivity.

transports pollutants, causes erosion, and reduces plant-available water; sediment originates from soil erosion; plant nutrients transported downstream are not available for crop production; and runoff losses reduce pesticide effectiveness. Cooperative research that combines downstream and source processes involved in soil erosion-soil productivity is needed to develop management models.

A modeling approach to research

Mathematical modeling and field experiments to support the models must be initiated to study the soil erosion-soil productivity relationship. The magnitude of the problem is so great that coordinated research involving USDA, the state agricultural experiment stations, universities, and the Cooperative Extension Services will be required to obtain a satisfactory solution. Objectives of the research should include (a) developing a physically based model capable of realistically simulating the processes that affect soil erosion and soil productivity; (b) applying the model to many areas throughout the United States to define the erosion-productivity relationship adequately; and (c) providing model outputs necessary for economic analyses concerning the value of soil loss.

The modeling approach has a number of advantages. First, it is efficient. Many years can be simulated quickly and relatively inexpensively for numerous locations and management strategies. Field experiments are time-consuming and costly, and the results are generally difficult to interpret.

Second, models are useful in determining long-term effects. Hundreds of years can be simulated practically using model-generated weather inputs. Third, an unlimited number of modern management strategies can be considered. Field experiments can only consider a few management strategies (usually those that are popular when the experiment is designed). Fourth, modeling is a learning exercise that increases knowledge about the processes involved.

Model components

Components of the erosion-productivity model should include hydrology, erosion-sedimentation, nutrient cycling, crop growth, tillage, and animal uptake for range and pasture.

The hydrology component must be capable of simulating evapotranspiration, percolation, surface runoff, and subsurface flow. It must properly describe soil water distribution through the root zone for accurate nutrient cycling and runoff prediction, and it must maintain a water balance.

The erosion-sedimentation component must operate on individual runoff events using rainfall and runoff inputs. It should simulate detachment of soil particles by rainfall, reentrainment of sediment particles in runoff, soil degradation by concentrated flow on uplands and in channels, and deposition. In addition to sediment yield, this component must calculate the particle-size distribution for use in simulating nutrient transport.

The nutrient cycling component must deal with nitrogen and phosphorus in both soluble and adsorbed forms. Necessary components of the nitrogen balance include leaching, runoff losses, crop residue, volatilization, denitrification, immobilization, mineralization, nitrification, crop uptake, rainfall contributions, and fertilizer. The phosphorus balance should include runoff losses, crop residue, crop uptake, fertilizer, plant availability, and adsorption-desorption. Processes that affect nutrient transport, such as sediment deposition and phosphorus adsorption-desorption, must also be simulated.

Crop growth components must be available for most important crops. These models must accurately simulate crop development (both above ground parts and roots), yield, and residue, given climate, water supply, and nutrients.

The tillage component must be capable

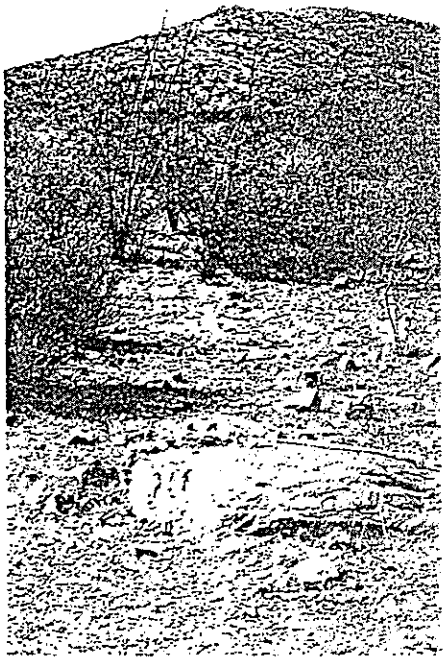
of simulating tillage effects on soil properties that affect hydrology, erosion-sedimentation, and crop growth. It must properly describe fertilizer and crop residue distribution through the plow layer.

The animal uptake component is needed to simulate grazing of range and pasture. It must be capable of predicting the effect of grazing on crop growth, evapotranspiration, runoff, erosion, and nutrient cycling. Accurate estimates of animal intake and output for various stocking rates will be required.

Model requirements

Individual model components must be completely compatible and capable of accepting input from and delivering output to other components. The complete model must meet nine criteria:

1. It must continuously simulate the processes involved, simultaneously and realistically, using a practical time step (probably daily).
2. It must be physically based and use readily available inputs. This eliminates models that require calibration because data, such as runoff, evapotranspiration, and sediment yield, generally are not available. If the parameters are physically significant, calibration is not necessary.
3. It must be able to compute the effects of management changes on outputs.
4. It must be able to predict crop yields accurately as erosion changes root-zone characteristics (removes upper soil layers and determines new root-zone depth dictated by subsoil conditions). This means that soil characteristics must extend considerably below the root zone at the beginning of the simulation.
5. It must be capable of estimating offsite effects, such as sediment deposition in waterways, channels, and floodplains and nutrient transport to streams and reservoirs.
6. It must be computationally efficient to allow simulation of various management strategies economically.
7. It must be capable of simulating long periods (hundreds of years) because erosion affects productivity very slowly in some cases. This requires a weather-generating submodel because long-term, measured values for variables, such as rainfall, temperature, and solar radiation, are generally not available.
8. It must have a built-in decision-making ability for adjusting management strategies as soil is eroded. For example, a soil originally in row crops may be converted to grass after a number of years of erosion because row cropping is no longer profitable.
9. It must be structured to permit easy component replacement when improved algorithms are developed.



Erosion removed nearly all of the soil on this Arizona watershed, making revegetation essentially impossible.

Model development

Models for most of the processes are in various stages of development. Once tested with existing data for validation, the models should be linked to form the erosion-productivity model.

Data for model development and validation will be obtained from existing data sources and from future experiments specifically designed to study the erosion-productivity relationship. Careful study of existing data from all sources (plots, fields, watersheds, floodplain deposition, etc.) should provide guidelines for designing future research programs and may reveal existing data suitable for testing models.

The next step is to establish a nationwide field experimentation program. Locations should be selected and experiments designed to maximize the information obtained.

Several factors are important in designing the field experiments. They include climate, crops, management practices (erosion control, fertilization, tillage, etc.), and land characteristics (soil type, topography, erodibility, state of erosion, productivity, etc.). The objective is to develop a network that represents typical agricultural conditions throughout the United States.

The validated model will provide information on accumulated erosion, annual crop yields, nutrient losses, annual fertilizer application rates, offsite sediment deposition, downstream nutrient yields to streams and reservoirs, and energy requirements for tillage and maintenance. From this output, accumulated erosion can be related to crop yield mathematically. Also, the monetary value of soil loss can be determined through reduced yields, increased fertilizer and energy requirements, and downstream damages.

Conclusions

Accurate estimates of soil productivity are essential in agricultural decision making and planning from a field scale to the national level. Until the relationship between erosion and productivity is adequately developed, selecting management strategies to maximize long-term crop production will be impossible. Poor decisions can easily result in serious damage to or under use of soil resources.

Research with the specific objective of determining the effects of soil erosion on crop production is limited. A few field experiments have demonstrated that erosion can drastically reduce crop yields. But this research is limited spatially (research in a few land resource areas represents a small fraction of the United States) and temporally (climatic variability is usually not representative of long-term variability).

Modeling research is also quite limited. Empirical relationships are difficult to develop because data are limited and because improved technology has masked the effects of erosion. Mathematical modeling based on physical processes is a more promising approach, but no physical models have been developed specifically for studying the erosion-productivity relationship.

Additional research, using mathematical modeling with field experiments to support the models, should ultimately permit the prediction of accumulated erosion, annual crop yields, nutrient losses, annual fertilizer application rates, offsite sediment deposition, downstream nutrient yields to streams and lakes, and energy requirements for tillage and maintenance. From this output, accumulated erosion can be related to crop yield mathematically. Also, the monetary cost of soil loss can be determined through reduced yields, increased

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