This paper was not peer-reviewed.
Pages 847-851. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory.

Keynote: Soil Erosion Prediction Technology for Conservation Planning

*George R. Foster**

ABSTRACT

Soil erosion by wind, water, and tillage can cause excessive on-site damage to landscapes and to the soil resources that make up landscapes and excessive damage to off-site resources that receive sediment produced by erosion. While certain land uses, like well-maintained pasture, satisfactorily control soil erosion in highly erosive conditions, putting these practices on every field is impractical. Significant erosion that would ordinarily occur with preferred land uses, like vegetable production on steep slopes, can often be satisfactorily controlled with well-chosen soil conservation technology.

Erosion is a complex process influenced by many variables including climate, soil, topography, and land use. The potential for erosion on one farmer's field can be very high, while very low on a neighbor's field. Additional complexity is that soils and off-site bodies receiving sediment from upstream sources can tolerate varying amount of erosion without excessive damage. Erosion is not easily measured, and even if it were, variations in the weather require a decade or two of measurements to accurately determine a long term, average annual erosion rate at a particular site.

Soil erosion prediction technology has proven to be a valuable tool for dealing with these complexities in conservation planning. Soil conservationists use this tool to develop conservation plans that take into account the erosion potential of specific sites, the impact of erosion on both on-site and off-site resources, and preferences of the land user.

On-Site and Off-Site Resources

Landscapes and their associated soils are valuable on-site resources used for many activities related to agriculture, forestry, rangelands, wildlife, recreation, military training, mining, energy production, construction, transportation, waste disposal, reclamation of disturbed lands, and conversion of land use. Protection against excessive erosion and maintenance of both the landscape itself and high quality soil across the landscape is necessary for long-term sustainability for both the resource and the land user.

Examples of off-site resources include air that receives dust from wind erosion and drinking water in a reservoir that receives sediment from both wind and water erosion. Sediment itself can be a pollutant and a carrier of other pollutants originating on farm fields where agricultural chemicals are used and from waste disposal sites. Sedimentation displaces volume in water conveyance structures like irrigation canals, stream channels, and reservoirs. This reduced capacity increases flooding, reduces water supply for irrigation, and hinders navigation.

Off-site impact can be immediately adjacent to the land unit where erosion produces the sediment such as fencerows and drainage ditches that collect sediment from wind, water, an tillage erosion. Or the impact can be remote in a community where breathing problems occur from dust, in an estuary at the outlet of a major river degraded by sedimentation, and at points between the origin of the sediment and its final destination.

Elements of Conservation Planning

Conservation planning for erosion control is the evaluation of alternative systems according to a defined criteria and choosing the one that best fits the situation. An acceptable conservation system must fit several requirements. Of course, the system must protect on-site resources, which include the landscape and the soils that make up the landscape, and off-site resources, which include air and water quality, water conveyance structures, reservoirs, and other places where sedimentation occurs.

The conservation system must accommodate a desired land use, which might be crop production, recreation, or waste disposal. The proposed system must be profitable, unless supported by funding from outside sources, and fit within the financial, managerial, and other resources available to implement new conservation technology. For example, without access to capital, implementation of technology that requires purchase of new farm implements or installation of elaborate terraces cannot occur. The conservation system must fit the scale of the land user. A system requiring large equipment does not fit small fields on steep landscapes.

The system must be culturally and socially acceptable. Cultural acceptability concerns range from "What will neighbors think and say?" to implement having features contrary to religious beliefs. Far more important than is frequently recognized are the personal preferences of the land user. Is the system convenient to farm and to manage? Will the land user like the proposed system? If the land user is not pleased with a proposed conservation system, the likelihood of long-term use and maintenance of the system is dramatically reduced.

Indices of Resource Well-Being

In general, conservation planning is choosing a system so that the detrimental impacts of erosion are within acceptable limits as defined by indices that indicate the well being of resources impacted by erosion. Several indices are needed,

*G.R. Foster, Agricultural Engineer (retired), USDA-Agricultural Research Service, National Sedimentation Laboratory, Oxford, Mississippi, USA. *Corresponding author: gfoster@spa.ars.usda.gov

because no single index addresses all erosional concerns associated with a resource. For example, maintenance of the ecological well being of rangelands is a high priority, and soil resources are critically important for supporting plant life. Protection of the soil against excessive erosion is necessary to maintain productivity and a diverse plant community. However, because rangeland ecology is related to other factors besides soil, consideration must be given to other processes besides erosion. That is, erosion control is not the sole interest in holistic conservation planning for any land use.

An index for well being of a resource must be understandable to those interested in the resource. The index must be measurable, and measurements must be repeatable and consistent. The index should be based on scientific knowledge, including how the index represents the quality of the resource and how environmental processes and land use affect the index.

The conservation planning process therefore involves the use of an index related to maintenance of the soil and a mathematical model to estimate soil erosion rates. A set of acceptable conservation systems are proposed in relation to conditions of the specific site and preferences of the land user. The mathematical soil erosion model is used to estimate an erosion rate for each alternative, and this rate is compared to values for indices used to represent the well being of on-site and off-site resources. The land user selects from those practices having estimated soil erosion rates that are lower than those considered to be acceptable.

Thus, two technologies are important. One is the erosion prediction technology and the second is the technology for the indices used to describe resource well being.

Indices for On-Site Impact of Soil Erosion

Erosion modifies soil properties by reducing soil depth, changing soil texture, and removing nutrients and organic matter. Erosion changes landscape properties by creating gullies, causing depositional areas, and amplifying soil differences across the landscape. While many indices can be used to describe the well being of soil and landscapes in relation to erosion, the soil loss tolerance index, T, is widely used.

The concept is that if soil erosion occurs at a greater rate than T, the soil will be excessively degraded. A T value is assigned to a soil based on the current state of the soil. Erosion must be controlled to a rate equal to or less that T to prevent excessive future degradation of the soil. The T value is not static, but changes as soil conditions change. Soil loss tolerance does not protect the soil from absolutely no degradation. Conservation planning is choosing a system having an estimated soil loss rate that is less than the T value.

The concept for soil loss tolerance and its use in conservation planning emerged in the U.S. in the mid-1940s. The concept was firmly established by the 1950s where the basic principles in assigning T values were set down and T values were assigned to many soils. The factors considered in setting T values include: rate of formation of the top horizon of soil from subsoil, formation of soil from parent material, depth of the soil profile, soil properties important for use of soil moisture by crops, loss of nutrients, change in soil texture by erosion, production of sediment that could leave the site and cause off-site damage, and the likelihood that rilling and gullies would develop. These elements are, for the most part, measurable.

Another element, just as important as these technical factors considered in setting T values, was the availability of conservation practices that farmers could use to meet T values while maintaining profitability without undue hardship. While the other factors are technical and scientific, this factor considers feasibility that the conservation technology can be implemented, government policy to encourage implementation of conservation, and economic and social considerations important to the land user.

Other on-site impacts of soil erosion are important besides removal of soil particles by erosion. Deposition occurs within many fields, which can harm a growing crop, and can change soil texture and other soil properties over the long term. Wind driven sediment from wind erosion can damage plant seedlings, reduce yields and sometimes require replanting.

The scientific resources devoted to erosion prediction technology far exceed those devoted to criteria for soil quality, including T values, and to understanding how erosion affects soil resources. Increased attention to understanding how soil erosion affects the well being of soil resources is greatly needed.

Indices for Off-Site Impacts of Soil Erosion

Indices for the off-site impacts of soil erosion are not nearly so well developed as soil loss tolerance T. Variables of great importance are the amount and rate of sediment reaching a given location and characteristics of that sediment. The degree that these variables are important depends on the situation. Fine sediment in the water is not a particular concern to navigation, but is a major concern where the water is being used for drinking or recreation. Dust in the air is of little concern in relation to fencerows at the edge of a field, but is a major concern for visibility on a roadway not far from the source of the dust. As a result, universal standards, like T values, have not emerged for use in conservation planning to control off-site impacts of erosion. A major complication in dealing with off-site impacts is determining the source of the sediment and how sediment characteristics are changed along the transport path from source to point of impact.

Conservation planning can occur on many spatial scales. If the concern is off-site such as for water quality in a reservoir or air quality in a community, the area of concern is the upstream area that produces the sediment and the delivery system. Planning is on a broad area basis and considers the variation of weather, soil, topography, and land use over the contributing region and how individual land units interact to affect sediment production and delivery. At some point in the planning process, attention becomes focused on individual land units because land users make management decisions at that level. If the concern is on-site, the attention is immediately focused on individual land units. Thus, most soil conservation planning is at the land unit level and most soil erosion prediction technology is targeted to that level. When estimated soil erosion rates are needed for multiple land units, the basic approach is to compute erosion rates at the land unit level and aggregate these values for large geographic units.

Soil Erosion Prediction Technology

Soil erosion prediction technologies are mathematical procedures that estimate rates of erosion and sediment delivery and sediment characteristics for specific sites as a function of weather, soil, topography, and land use. These technologies vary according to underlying concepts on which the procedures are based, the processes and effects represented by the procedures, the governing equations, the mathematical structure that connects the equations, and the variables for which computations are made. Estimated values for the same variable can differ significantly among soil erosion models.

Soil erosion prediction technologies can be classified as being in one of two broad categories of lumped process-based or fundamental process-based. In the lumped process-based models, the underlying mathematical structure typically represents main effects with a set of indices and parameter values that have been empirically derived. The intent is not to describe erosion processes but to describe the main effects of the variables that affect erosion processes. In the fundamental process-based model, individual erosion processes are explicitly described, and effects of variables on soil erosion are described by how these variables affect the fundamental processes represented in the model.

All erosion models, regardless of their underlying structure, require empirical data. Even the most scientifically advanced models require empirical data to determine values for parameters such as soil erodibility if these models are to be used in conservation planning.

The requirements for erosion models vary according to the intended purpose of the model. The requirements for a model used in a scientific study of erosion differ greatly from those for a model used in routine conservation planning by field personnel.

Requirements for Erosion Prediction Technology for Conservation Planning

Applicable to the situation. The model must apply to the erosion processes being considered in the planning process. That is, a model designed to compute sheet and rill erosion generally cannot be used to estimate gully erosion.

Consistent and repeatable results. The model must use parameters where consistent input values are chosen by the same or multiple users for the same or similar situations. While land users may not be able judge absolute values of soil loss estimates, they can easily judge the consistency of estimated values. Inconsistent results dramatically diminish the creditability of a model.

Covers full range of applications. Users strongly prefer a single model that applies to all of the situations where erosion is a concern in their conservation planning activities. Having to use separate models causes problems for situations where the models overlap because results from models often differ.

Easily used with available resources. Models require resources to use. These resources include computers, expertise and time required to use the model, and availability of input data. If the resources required to use a model exceed the perceived value of the results from the model, the conservation planner will resist using a particular model.

Valid. The model must be valid.

Validity

Validity of erosion prediction technology for conservation planning is very much misunderstood. The proper definition of validity is that the model serves its intended purpose.

Too frequently and incorrectly, validity is judged solely on how well estimates from a model fit measured research data. While measures of how well estimates from a model fit measured data are important, these measures alone are incomplete and inadequate for determining how well a particular model fits the needs of conservation planning.

Research data used to develop erosion models are often incomplete, and frequently the data do not cover a sufficiently broad range of conditions. For example, very few data are available on the decay of ridge height, and most of these data are from regions where wind erosion rather than water erosion is the major problem. When equations fitted to those data are extrapolated to regions where water erosion is the primary concern, the equations estimate incorrect values. When the equations are changed to give intuitively reasonable results for high precipitation regions, the quality of the fit of the equations to the available research data is decreased. The second set of equations with adjustments for high precipitation are more valid for conservation planning than the first set of equations, even though the first set of equations fits the research data better than does the second set.

Erosion research data are highly variable, and far too few replications are available to achieve narrow confidence intervals for statistical measures of goodness of fit. However, the data are entirely adequate for defining the trends produced by major effects when judged as a whole and when analyzed using proven scientific principles. Accurately describing trends based on accepted scientific principles is often more important than how well the model fits the research data. For example, a particular set of data, which is somewhat small considering the number of variables involved, might be used to validate erosion models. This particular data set seems to indicate, on first analysis, that erosion increases as ground cover increases, an obviously unacceptable result based on other research. To force an erosion model to fit these data regarding how ground cover affects soil loss would result in a flawed model. The many interactions between key variables in this small data set prevents the true relationship among variables from being well represented.

Choosing a Model

Several considerations are involved in choosing a model for use in conservation planning. The user requirements mentioned above provide a partial basis for the choice. Select a model that serves the intended purpose because some models don't provide certain estimates such as characteristics of sediment leaving a land unit, or some models don't apply to a particular process, like erosion caused by surface irrigation. Another important consideration is whether a possible model describes the main effects of interest.

Skill of the model developer and model user are typically more important than the model itself and the science on which it is based. The purpose of a model for conservation planning is not to describe erosion processes but to describe the main effects of variables that affect erosion. All models are based on a particular set of assumptions. A model based on the assumption of a uniform slope can have elaborate equations for erosion processes, but it will perform poorly when applied to non-uniform slopes.

All models are empirical in that data are required to calibrate parameter values, with the result that differences among models are significantly reduced when fitted to and validated with the same experimental data. Also, all erosion models must be extrapolated beyond the research data used to derive them. When extrapolated, a well-done empirical model will outperform a highly theoretical model if the theoretical model does not use robust relationships. Although the problem of extrapolating empirical models beyond their research data is well recognized, similar difficulties exist with fundamental process-based models, but are often not recognized. Construction of the governing equations and the model structure, which reflect the skill of the model developer, rather than the model type are key factors.

The chosen model should be consistent with the available resources required to use the model in terms of available parameter values, input data, technical ability to run the model, training opportunities, computer equipment, and time required to make a set of computations for developing a conservation plan. Do not give high priority to a model if the values of the estimates from it do not measure up to the resources required to use the model. Also, do not give high priority to a model if estimates from it are similar to those from another model that requires fewer resources.

Considerable art is involved in using models for conservation planning. Model users learn from experience how to choose parameter values and how to apply the model in relation to field conditions. The skill of the model user often overcomes model deficiencies. Just as land users prefer "comfortable" conservation practices, conservationists prefer "comfortable" erosion prediction technology. "Comfort" sometimes relates to being able to understand how the model works, but it simply may be no more than a personal preference for or previous experience with a particular model.

In making a final decision in the choice of a model, if two models result in the same planning decision, the two models are the same performance wise, and the choice is based on other considerations, such as preference.

Importance of Model Structure

The governing equations used in a model are critically important, but equally important is model structure. Unfortunately, model structure does not receive sufficient attention. Problems with model structure are most apparent when dealing with non-uniform conditions because of the non-linearity common to erosion relationships. For example, the effect of ground cover on erosion is very nonlinear. To illustrate, consider a surface where the cover occurs non-uniformly in patches or in strips. A model structure based on the assumption that the cover is uniform gives a very poor estimate.

A far better model structure is to divide the model into two components, one for the area where the cover is low and the other where the cover is high. A uniform cover of 50 percent might give a soil loss of 8. For a surface having two areas, one with a cover of 10 percent and the other with a cover of 90 percent, the soil loss would be 31 where the two areas are properly considered individually. The soil loss from a model based on an average cover, 50 percent in this case, rather than considering the two areas separately estimates soil loss that can be in considerable error, about one third of the appropriate value for this example.

This example illustrates how a poorly structured model, even though based on the best scientific equations for describing erosion processes, gives poor results. It also illustrates how problems can arise for estimating soil loss for a large, highly variable area. Taking an average of the input values and entering them into the model will give very poor results because of nonlinear governing equations. The proper way to compute average soil loss for a large area is to compute soil loss at many points based on conditions at each point and then aggregate the results. Although erosion prediction technology has been incorporated into geographic information systems (GIS) for many years, the erosion predictions from these systems are often questionable because of failure to consider the nonlinear equations used in erosion prediction technologies in relation to variability to weather, soil, topography, and land use in space.

Transferability

A common question is whether a model developed from research data collected in one geographic region can be transferred for use in another region. Choosing an existing and extensively used model should be a first consideration. An organization that has long used a particular model will have acquired a well-developed set of parameter values and guidelines for using the model. The organization will have discovered problems with the model, fixed them, and developed the "art" for applying the model.

In transferring a model to a new region, weather data will have to be assembled and analyzed in almost every case. A major consideration is whether the required weather data can be readily obtained.

Information will also have to be obtained for soils. Some of the governing relationships for soils in erosion models can often be transferred, but because information on soils is so strongly empirical, the relationships related to soils should be examined carefully before adopting a particular model.

Relationships and parameter values associated with plants and mechanical operations seem quite transferable. However, the relationships must be carefully inspected, especially when a crop growth model is being used in the erosion model.

In some ways, process-based models can be more confidently transferred than the lumped process-based models. However, interestingly the theoretical components of these models sometimes make these models more difficult to transfer than simple, empirical, lumped process-based models. The final decision is often a judgment call. The skill of both the technical staff doing the transfer and the users can be more important than the model itself.

How Good are Erosion Models

Erosion prediction technology is controversial. Erosion prediction technology has been criticized in general and certain models in particular have been criticized. While some of the criticism is valid, it has also been misdirected. Erosion prediction technology should be used as a guide for conservation planning. The planner does the planning. The erosion prediction technology provides information to assist in the planning that would not be available otherwise.

Also, almost all erosion prediction technologies do a good job of describing main effects. Problems arise when erosion prediction technology becomes too rigidly used in regulation-type of applications. Sometimes models are misused in conservation planning such as trying to estimate ephemeral gully erosion with a model that only estimates sheet and rill erosion. Criticisms of this misuse are valid. Erosion models are sometimes criticized for not fitting measured research data very well without consideration of how well the model estimates main effects that are well accepted by the scientific community or without consideration for the quality of the observed data. Such criticism is misdirected. Sometimes erosion prediction technology is criticized when the concern seems more related to a particular public policy than to the adequacy of the technology.

Conservation planning is to support and encourage conservation, identify areas where erosion is excessive, and to develop acceptable conservation plans that are readily accepted. Erosion prediction technology has proven to be a valuable tool in guiding these conservation activities, and it must be judged in that context.

Future for Erosion Prediction Technology

The market place will continue to support a variety of erosion prediction technologies ranging from very simple to very complex models. Computers and use of databases will become more widely used and will make erosion prediction technology easier to use. Integration of erosion prediction technology into geographic information systems (GIS) will become increasingly common. Many applications for erosion prediction technology involving GIS, global positioning systems, and data acquisition systems can be imagined. These applications are rapidly developing, but stand alone, simple erosion prediction technology will still be widely used for the next decade.

Development of the underlying science that supports erosion prediction technology needs a boost. Erosion science seems to be lagging. An extensive modern database is needed to replace the widely used but obsolete database developed mainly during the 1930s through the 1960s. Certain erosion prediction technology is rightfully criticized for being based on this obsolete database. Erosion research technology needs development so that erosion data can be collected that has far less variability between replications than is in current data. While not cutting edge science, information is needed on several "small" items like decay of roughness and ridge height as a function of weather, soil, and management variables; how soil erodibility changes over time after a mechanical disturbance of the soil; and how management affects soil erodibility. While sufficient scientific information may be available to indicate that an effect exists, far too little data exists to develop mathematical relationships needed in erosion models that are to apply over large, highly variable geographic regions.

Improved ways of dealing with non-uniformity and scale are needed, especially in dealing with infiltration, runoff, hydraulics, and wind mechanics in relation to variations in surface conditions and topography. New creative thinking is needed for model structure, which could result in major improvements in models.

Perhaps more important than research related to erosion prediction is development of a modern procedure to replace soil loss tolerance. Research in the whole area of indices needed to evaluate the impact of erosion has seriously lagged.

SUMMARY

Used as a guide, erosion prediction technology along with soil loss tolerance and other indices of impact is a powerful conservation-planning tool. Conservation planning is far superior when erosion prediction is used. The quality of results from erosion prediction in conservation planning depends on having well trained personnel, well done guidelines, and readily available input data. Several erosion prediction models exist, and no single model is best in every aspect. Choose a model that best fits the situation and is preferred by users. A variety of models will continue to exist as a variety of users express a variety of preferences.

ACKNOWLEDGMENT

This paper was developed under a joint agreement with the USDA-Agricultural Research Service and the Natural Resources Conservation Service, Washington, D.C. and the University of Tennessee, Knoxville.