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DEVELOPMENT OF A NEW WIND EROSION PREDICTION SYSTEM[1]

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ABSTRACT: New developments in erosion science are being coupled with data bases and new computer technology to generate what should be a significant advancement in wind erosion prediction technology. This report presents an overview of user applications for the prediction technology, along with a proposed model structure to meet user requirements. The structure is modular, and major submodels deal with weather generation, crop growth and decomposition, tillage, soil temporal properties, soil water and energy balances, and wind erosion mechanics. An example calculation of average erosion losses on a 100 m long field as a function of loose-erodible surface soil and abrasion coefficients of crust or aggregates also is included. Model validation will be accomplished using computer analyses; plot studies; and instrumented, eroding fields.

INTRODUCTION: Wind erosion is a serious problem in many parts of the world, and human impact on global desertification is an issue of current international concern (SECRETARIAT of UNCOD, 1977). Arid or semiarid lands now comprise about one-third of the world's total land area and are home to about one-sixth of the world's population (DREGNE, 1976; GORE, 1979). However, intensive soil tillage, harvest of crop residues, and production of low residue crops often extend the wind erosion problem beyond semiarid to more humid regions. Thus, development of adequate prediction technology for wind erosion is important to provide producers with guidance in the use of these potentially erodible lands.

In the United States, the primary technology currently used for predicting wind erosion is based on variations of the Wind Erosion Equation (WEQ) (WOODRUFF and SIDDOWAY, 1965). This prediction system involves integrations over large fields with unchanging surface conditions and long time scales to produce average, annual estimates of soil loss. The current system represents a mature technology, which is not easily adapted to untested conditions or climates far different than that of the Central Great Plains of the USA where the WEQ was developed. However, new developments in erosion science and the increased availability of powerful personal computers, would allow most users of erosion prediction technology to adopt a flexible, process-based, erosion prediction technology.

Recently, the U.S. Department of Agriculture appointed a team of scientists to take a leading role in combining erosion science with data bases and computers to develop what should be a significant advancement in wind erosion prediction technology. The objective of the project is to develop a new Wind Erosion Prediction System (WEPS) as a replacement technology for

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the WEQ. In this report, an overview of the applications for wind erosion prediction technology is presented, along with a proposed model structure and validation procedure to meet user requirements.

PREDICTION TECHNOLOGY APPLICATIONS: Among the most important applications for wind erosion prediction technology is conservation planning of wind erosion control practices to assist farmers and ranchers in meeting erosion tolerances. Conservation planning in field offices requires a prediction system that will operate on a personal computer, use readily available inputs, and produce answers in a relatively short time. In addition, a WEPS must serve as a communication tool between conservation planners and those who implement the plans. In another application, data are collected at primary sampling points as part of national resource inventories, and erosion losses occurring under current land-use practices are calculated. The analyzed results are used to aid in developing regional and national land use policy.

Various users of wind erosion prediction technology undertake project planning, in which erosion and deposition are evaluated in areas impacted by a proposed project. Researchers also frequently need a physically based prediction technology to assist them in evaluating proposed, new, erosion control methods. The prediction technology should allow them to make low-cost simulation tests of various combinations of erosion control practices in a variety of climates.

Other users of wind erosion prediction technology investigate a wide range of problem areas. Often, their applications will require development of additional models to supplement WEPS in order to obtain answers of interest. Some of these diverse problem areas include estimating long-term soil productivity changes, determining physical damage to plants, calculating on-site and off-site economic costs of erosion, finding deposition loading of lakes and streams, computing the effects of dust on acid rain processes, determining impact of management strategies on public lands, and estimating visibility reductions near airports and highways.

OVERVIEW OF MODEL: WEPS will be a daily simulation model written in FORTRAN 77 and based on physical principles of the relevant processes. The user interface section of WEPS will provide menus to facilitate preparation of user input files and be written in C language.

In the model, the simulation region will be a field or, at most, a few adjacent fields. Model outputs will be average soil loss/deposition over the accounting region for a user-selected time interval. The model also will have an option to provide users with individual loss components for the creep, saltation, and suspension fractions, as well as individual accounting for deposition of creep and saltation fractions.

The structure of WEPS is modular and consists of a MAIN (supervisory) program, a user-interface input section, seven submodels along with their associated data bases, and an output control section (Fig. 1). MAIN has two major functions. First, it calls the subroutines that control preparation of the user input files. Second, it controls the sequence of events in the simulation runs.

The framework of the user interface in WERM is composed of the input/output forms control section and two levels of input parameter files. The control section will use a series of menus and submenus to guide the user in preparing run files, which contain all the input parameters needed for single or batch simulation runs. The run files can be created by direct input from the keyboard, by recall and editing of existing run files, or by assembly of second-level submodel input and data base files. The submodel files consist of input files needed by individual submodels and correspond to sections of the run file. These can be individually prepared, edited, stored, or assembled to form complete run files. Another important function of the user interface section is selection of output options.

The modular structure permits members of the modeling team to easily test and update specific sections of the model during development. It will also facilitate model maintenance as new technology becomes available. In general, the submodels are based on fundamental processes occurring in the field. Extensive experimental work is being carried out simultaneously with model development and is mainly devoted to delineating parameter values that control the processes.

SUBMODEL CONCEPTS: Because the model deals with prediction of future events, the objectives of the CROP GROWTH, DECOMPOSITION, SOIL, HYDROLOGY, and TILLAGE submodels are to predict the temporal soil and vegetative cover variables that control soil erodibility in response to inputs generated by the WEATHER submodel. Finally, if wind speeds are above the erosion threshold, the EROSION submodel computes soil loss or deposition and new estimates of soil and plant variable values over the simulation region. The function of each submodel and its data base will now be outlined in more detail.

WEATHER:

The WEATHER submodel will generate meteorological variables needed to drive the CROP GROWTH, DECOMPOSITION, HYDROLOGY, SOIL, and EROSION submodels. The weather generator developed to drive the Water Erosion Prediction Project (WEPP) family of erosion models (NICKS et al., 1987) likely will be used as part of the WEATHER submodel. That generator currently generates daily duration, intensity, and amount of precipitation; maximum and minimum temperature; solar radiation; and dew point. The generator will be capable of generating a design storm, a selected storm, or continuous simulation. Efforts to develop generators for wind speed and wind direction also have been completed (SKIDMORE and TATARKO, 1990). For the EROSION submodel, maximum daily wind speeds are needed to determine if any erosion will occur. If erosion can occur, then wind speed and direction must be generated at subhourly intervals during erosion events.

The WEATHER data base will consist of sets of monthly statistical parameters, which describe the generated weather variables. The parameters have been developed for 1000 U.S. stations for the WEPP weather generator. The data base of stations reporting wind data is somewhat less, but the available data base of wind stations also has been parameterized.

CROP:

Biomass accounting in the model is accomplished by a CROP GROWTH submodel and a DECOMPOSITION submodel. Crop growth will be simulated by a generalized growth model, which calculates potential growth of leaves, stems, yield, and root components. The potential growth will be modified by both temperature, fertility, and moisture stresses. A modified version of the EPIC growth model (WILLIAMS et al., 1984) has been adapted to accomplish these tasks. Pests and diseases will not be considered as limiting factors.

As input for the EROSION submodel, the CROP submodel will provide the distributions of leaf and stem silhouette area with height, canopy height, canopy cover, and flat biomass cover. Prediction equations for several of these variables in a number of crops have been developed using biomass as the independent variable (ARMBRUST and BILBRO, 1988). The need to distinguish between leaf and stem area arises because leaves tend to streamline with the flow and have a drag coefficient (C_d) of about 0.1, whereas stems tend to remain rigid and have a C_d of about 1.0. Thus, on a unit area basis, stems are about 10 times more effective than leaves in depleting the wind force transmitted to the canopy.

The CROP data base will contain information on specific crops and include parameters on growth, leaf-stem relationships, decomposition, and harvest.

DECOMPOSITION:

The DECOMPOSITION submodel will keep account of the biomass residues in standing, flat, and buried categories. Such factors as crop carbon-nitrogen ratios, temperature, and moisture will be used to drive the rates of decomposition. In addition to the biomass flow paths, there will be a biomass sink called harvest, initiated by the TILLAGE submodel, which will remove biomass from some of the categories.

SOIL:

The role of the SOIL submodel is to modify, on a daily time step, temporal soil profile properties (Table 1) between erosion and tillage events. The soil surface configuration is treated as having both oriented and random roughness components, which will be updated separately. This is necessary because the effective deposition capacity, aerodynamic roughness, and soil transport capacities all vary as a function of wind direction relative to an oriented roughness such as tillage ridges. The temporal soil properties and surface roughness depend on both intrinsic properties, such as texture and secondary temporal properties, as well as on climate and management factors (ZOBECK, 1987; SKIDMORE and LAYTON, 1988).

The SOIL data base will consist of the intrinsic soil properties that are shown to be useful in predicting the temporal soil properties.

HYDROLOGY:

The function of this submodel is to simulate the soil water and energy balances. In order to assess the water balance, this submodel will account for infiltration, snowmelt, runoff, deep percolation, evaporation, and plant water use. Water added by irrigation will be distributed through the soil profile, and soil subsurface drainage by tile will be approximated. Wind redistribution of snow also will be accounted for in this submodel. Snowmelt is calculated using an equation for melt in open areas as modified by HENDRICK et al. (1971). Potential evaporation is calculated using a combination method (VAN BAVEL, 1966) and then adjusted using Darcy's law of soil water flux to obtain actual evaporation. Runoff is calculated as precipitation exceeding the infiltration rate, assuming that the simulation region is composed of subregions of constant slope. Deep percolation from the soil profile is estimated to be equal to the conductivity of the lowermost soil layer, assuming a unit hydraulic gradient.

The soil energy balance will be calculated, and the soil temperature profile will be computed. Soil freeze/thaw cycles and frost depth also will be simulated, as proposed by BENOIT and MOSTAGHIMI (1985).

TILLAGE:

The roles of the TILLAGE submodel are to assess the effects of tillage on both temporal soil properties and surface configuration for delivery to the HYDROLOGY and SOIL submodels and to determine biomass manipulation for delivery to the CROP and DECOMPOSITION submodels. The primary temporal soil properties that control the wind erodibility of the soil, along with biomass manipulation and surface configuration, are to be predicted. Predictions will use regression-type equations, in which the independent variables likely will fit into three categories: (a) initial conditions, (b) tillage tool (machine) parameters, and (c) physical soil properties. Simulation of the soil manipulations by tillage tools is being grouped into four categories--mixing, loosening, inverting, and crushing (COLE, 1988). Random roughness will be predicted by the submodel, whereas height, spacing, and orientation of oriented roughness will be input by the user.

The TILLAGE submodel input files will consist of user-developed schedules of tillage events, and the TILLAGE data base will consist of tables of parameters for specific tillage and harvesting machines.

EROSION:

The EROSION submodel will perform several major tasks. The first task is to compute the surface threshold friction velocities over the simulation region, considering the effects of flat cover, surface roughness, and primary temporal soil properties. The second task is to compute field surface friction velocities based on the wind speed and direction supplied by the WEATHER submodel, considering the effects of hills, barriers, standing canopies, and surface roughness.

During periods when friction velocity exceeds the threshold level, soil loss and deposition will be computed over the simulation region at subhourly intervals (Fig 2). Soil transport by wind erosion is modeled as the time-dependent conservation of mass of two species (saltation- and creep-size aggregates) with two sources of erodible material (emission and abrasion) and two sinks (surface trapping and suspension). In addition, the soil surface conditions are updated periodically in response to the soil loss or deposition that has occurred.

The source and sink terms represent distinct physical subprocesses that can occur during wind erosion. Emission occurs when there is a net loss of loose, saltation/creep-size aggregates caused by a combination of wind shear and saltation impact forces. This loss is typical of the data obtained in wind tunnel tests on soil aggregates (CHEPIL, 1950, 1951; FRYREAR, 1984). Trapping occurs when there is a net deposition of saltation/creep-size material over a portion of the surface, such as between ridges (HAGEN and ARMBRUST, 1989). Abrasion is used here to mean the breakdown of nonerodible-size clods and crust to wind-erodible sizes. This subprocess depends on the horizontal flux of saltating aggregates, the stability of the target, and other factors (HAGEN, 1984,1991).

Sources of the suspension-size material include direct emission from among the soil aggregates, as well as creation of additional material abraded from the clods, crusts, and impacting aggregates during erosion (HAGEN and LYLES, 1985). The magnitude of the suspension component varies widely among fields (GILLETTE, 1977). In the model, the suspended material is regarded as lost through the top of the control volume, and its deposition is not considered, because it generally occurs over a much larger area than that encompassed by the simulation region.

In the EROSION submodel, standing vegetative biomass has three major effects on soil movement. First, the structure of a canopy gives rise to its aerodynamic roughness, which determines the friction velocity at the top of the canopy for a given wind speed. Second, leaves and stems deplete a portion of the friction velocity through the canopy and, thus, control velocity near the surface. Finally, if the surface friction velocity exceeds the threshold, vegetation intercepts some of the saltating particles in flight to further reduce soil movement.

Flat residues are treated as creators of surface cover, and their diameter increases roughness. Thus, flat residues modify aerodynamic surface roughness, protect part of the surface from both abrasion and emission, and may enhance surface trapping.

The complete conservation equations for the bare soil control volume are presented elsewhere (HAGEN, 1991). However, one can use simplified equations to develop an initial quantification of some wind erosion processes. To illustrate, we will calculate the maximum soil removal possible from simple, bare, soil surfaces with a unidirectional wind. As a first example, consider a uniformly crusted surface with some loose soil grains on the surface. Total loss has the form

$$dQ/dx = (G_{en} + G_{an})\,T \tag{1}$$

where

- Q - Total saltation discharge,
- x - distance along the wind direction,
- G_{en} - vertical emission flux,
- G_{an} - vertical abrasion flux, and
- T - total time to field stability.

But

$$G_{en}T = E_o \tag{2}$$

and abrasion studies (HAGEN, 1991) demonstrate that

$$G_{an}T = \overline{F_{an}C_{an}}\,Q \tag{3}$$

where

- $\overline{F}_{an}$ - the average fraction of abrader impacting the crust,
- $\overline{C}_{an}$ - the average abrasion coefficient for the crust, and
- E_o - the loose, erodible particles on a crusted surface per unit area.

Average soil loss per unit area is then

$$\frac{Q_L}{L} = \frac{E_o}{L\overline{F_{an}C_{an}}}(\exp(L\overline{F_{an}C_{an}}) - 1) \tag{4}$$

where

L - field length along wind direction.

Equation 4 remains valid, so long as the abrader does not penetrate below the consolidated crust zone.

Next, consider a newly tilled surface with uniform distribution of erodible and non-erodible aggregates. For such a surface, total loss along the wind direction is:

$$dQ/dx = (G_{enz} + G_{en} + G_{an})\,T \tag{5}$$

where

G_{enz} - the vertical flux of erodible particles that are initially sheltered by non-erodible aggregates.

After removal of the unsheltered, loose particles, the emission loss and abrasion loss must be proportional to their respective volumes, V_{en} and V_{an}, such that

$$\frac{G_{enz}}{\overline{F_{an}C_{an}}Q} = \frac{V_{en}}{V_{an}} \tag{6}$$

Then, let

$$C2 = \left[1 + \frac{V_{en}}{V_{an}}\right]\overline{F_{an}C_{an}} \tag{7}$$

and, similar to the crusted surface solution, average soil loss is

$$\frac{Q_L}{L} = \frac{E_o}{LC2}\left(\exp(LC2) - 1\right) \tag{8}$$

Numerical solutions of equations 4 and 8 were calculated for constant levels of soil loss on a 100 m long field. Results in Figure 3 would be typical of crusted surfaces with average abrasion coefficients ranging from 0.01 to 0.10. ZOBECK (1991) used a rainfall simulator to fabricate crusts on a range of soils and reported that the abrasion coefficients ranged from about 0.01 to more than 0.10. POTTER (1990) measured loose, erodible particles present on crusted field soils treated with a rainfall simulator and found that the loose soil ranged from 0.003 kg/m^2 on fine textured soils to 0.091 kg/m^2 on coarse textured soils. However, inspection of Figure 3 shows that even low amounts of loose particles on surfaces with an abrasion coefficient above 0.10 will cause excessive erosion.

Soil aggregates tend to have lower abrasion coefficients than soil crusts (CHEPIL and WOODRUFF, 1963). Thus, calculations in Figure 3 for C2 values less than 0.02 are typical of aggregated surfaces. However, these tend to have large amounts of loose soil, which can begin the abrasion process. For example, at a friction velocity of 0.61 m/s, CHEPIL (1951) measured wind tunnel emissions of 2.5, 6.1, and 14 kg/m^2 of fine particles from trays containing 20, 10, and 4 percent aggregates greater than 0.84 mm diameter, respectively. Thus, knowledge of both aggregate size distribution and aggregate abrasion coefficients are generally needed to predict the potential soil loss from a bare, aggregated field.

In the preceding examples, a 100 m field length was selected. But, as field length increases, the crust/aggregate abrasion coefficients become dominant factors in determining soil loss. However, as field length decreases, the loose material available for emission becomes the dominant factor controlling potential soil loss on smooth, bare fields.

VALIDATION: The submodels will be validated using various methods. The weather series generated by the WEATHER submodel will be compared to actual-weather time series to ensure that both produce similar statistical parameters. Recorded meteorological variables will be input to the model, to compare the temporal soil properties predicted by the SOIL and TILLAGE submodels to measured soil properties in plot studies. Similarly, biomass patterns of some major crops will be compared to biomass production predicted by the CROP submodel and biomass reduction predicted by the DECOMPOSITION submodel.

Finally, the EROSION submodel will be validated by instrumenting a series of field-scale sites. This appears necessary, because the equations describing the erosion subprocesses are being developed in laboratory wind tunnels on individual subprocesses. In the field, the subprocesses are combined and operate over larger scales than in the laboratory. Initial field-scale validation sites are in operation in the states of Texas, Montana, Colorado, Nebraska, Minnesota, Indiana, Washington, and Kansas (FRYREAR et al, 1991).

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Table 1. Primary, temporal soil properties that control soil wind erodibility.

Soil Fraction	Properties
All	Surface wetness Bulk density Surface microrelief
Aggregates	Size distribution Dry stability Density
Crust	Thickness Dry stability Loose soil above Cover fraction Density

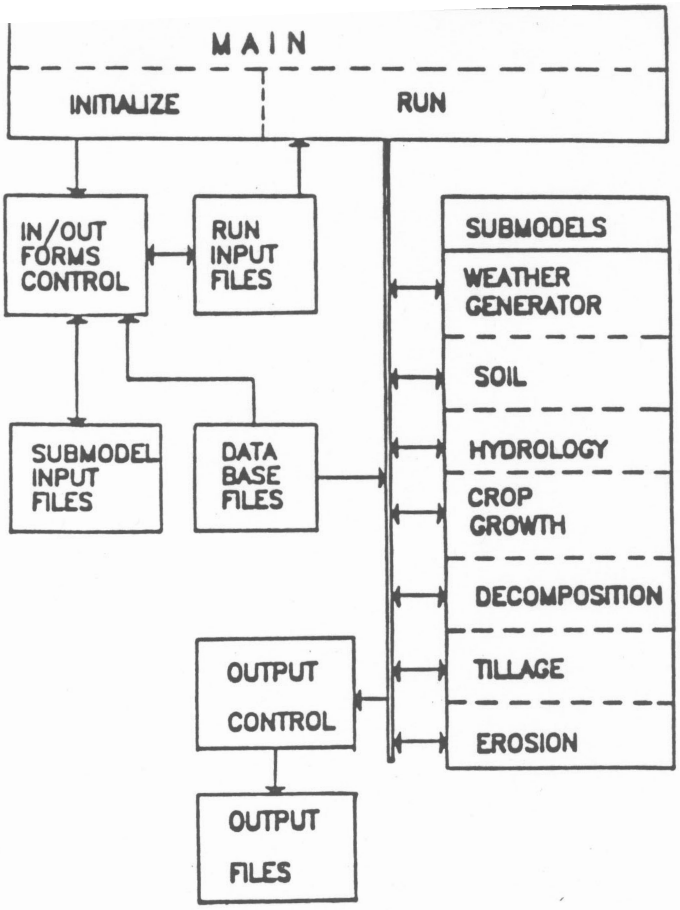

Figure 1. Diagram of WEPS with user interface, data bases, and submodels.

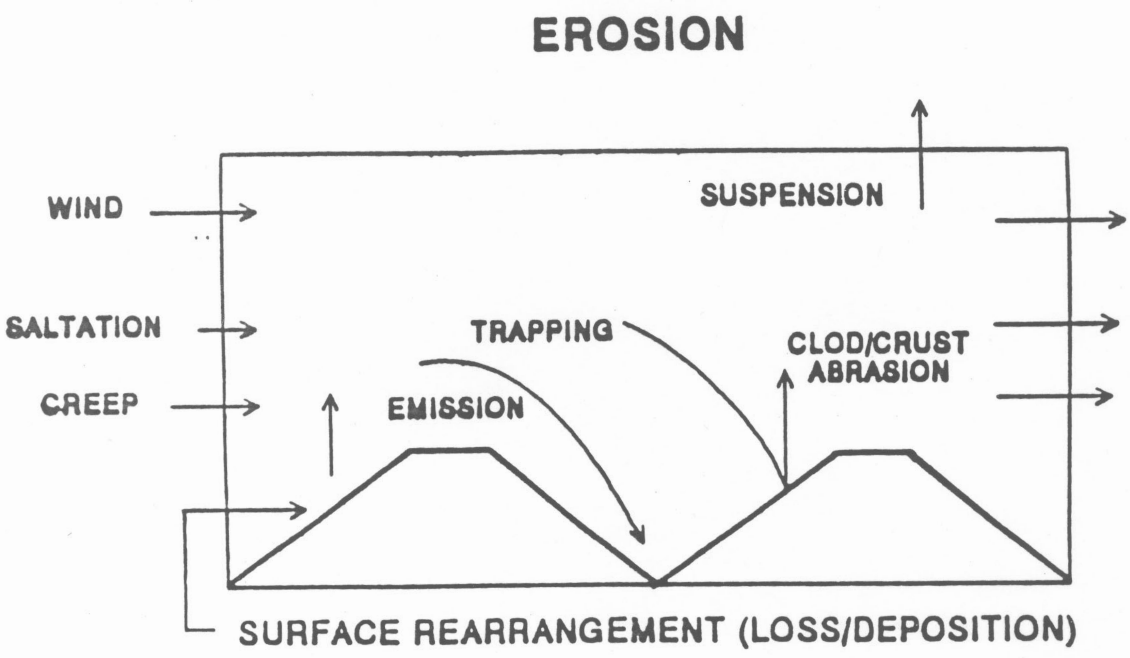

Figure 2. Diagram of a control volume for EROSION submodel with bare soil.

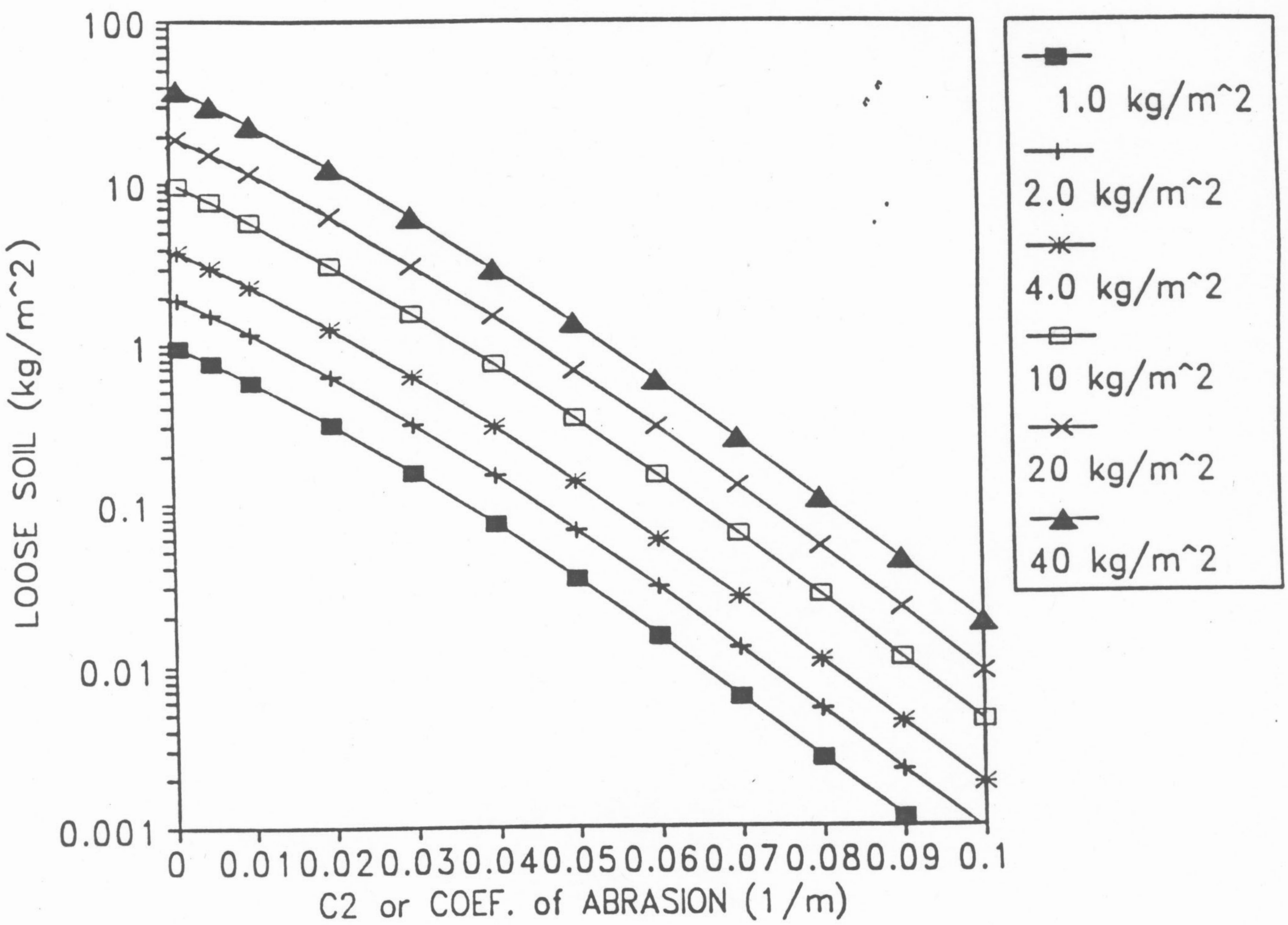

Figure 3. Calculated maximum potential soil losses averaged over a 100 m long field as functions of loose, erodible surface soil and abrasion coefficients of crust or aggregates.