Wind Erosion Prediction System: Management Submodel[1]

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Introduction

The Wind Erosion Prediction System (WEPS) is a process-based, daily time-step model that simulates weather, field conditions, and erosion. WEPS development is in response to customer requests for improved wind erosion technology. It is intended to replace the predominately empirical Wind Erosion Equation (Woodruff and Siddoway, 1965) as a prediction tool for those who plan soil conservation systems, conduct environmental planning, or assess offsite impacts caused by wind erosion. WEPS incorporates improved technology for computing soil loss by wind from agricultural fields as well as providing new capabilities such as assessing plant damage, calculating suspension loss, and estimating PM-10 emissions from the field (Wagner, 1996).

As a process-based planning tool, WEPS is expected to reflect the effects of various management practices upon wind erosion. Therefore, the WEPS MANAGEMENT submodel's objective is to simulate those management practices. For WEPS to accurately assess management effects upon a site's susceptibility to wind erosion, the MANAGEMENT submodel must adequately simulate the diverse cultural practices employed by producers. Those practices include typical primary and secondary tillage, cultivation, planting/seeding, harvesting, and fertilization operations as well as irrigation, burning, and grazing practices.

Submodel Description

The MANAGEMENT submodel deals with the variety of land management actions by identifying the primary physical processes involved and representing each individual management operation as a sequenced set of those primary physical processes. Those processes include: 1) mass manipulation (changes in aggregate size distribution and soil porosity, mixing of soil and residue among soil layers, and soil layer inversion); 2) surface modification (creation or destruction of ridges and/or dikes that form oriented surface roughness, changes in surface random roughness, and destruction of soil crust); 3) biomass manipulation (burying and resurfacing residue, clipping standing residue, flattening standing residue, killing live crop biomass, and biomass removal); and 4) soil amendments (fertilization, planting, and irrigation).

In accord with the WEPS design philosophy, the MANAGEMENT submodel simulates these processes via a physical basis if possible, incorporates conservation of mass and energy concepts, and employs a minimum of parameters with readily available and/or attainable values. These processes are assumed to be independent with respect to each other and are simulated sequentially. Each management operation thus is represented by an appropriate list of processes.

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The individual processes and their order of simulation describe each specific operation.

The list of management operations performed for a given management plan (crop rotation or cyclical list of cultural practices) is specified in a MANAGEMENT input file. On the dates when operations are to be performed, the MANAGEMENT submodel will execute the specified routines required to simulate the effects of those operations as instructed in the MANAGEMENT input file. When the final operation is performed for that particular crop rotation cycle, the sequence will be repeated for the next year(s) of the simulation.

Physical Processes Modeled

In WEPS, spatial variability is handled through the use of subregions. Hence, in each subregion, the submodel considers the soil mass, surface, and biomass properties to be homogeneous in a horizontal plane yet variable in the vertical direction (soil layers).
The soil surface is considered to include various combinations of random roughness, ridged, or ridged and diked. Live (crop) and dead (crop residue) biomass may exist in the soil and on the surface in standing and/or flat orientations.

A concept utilized throughout equation development has been that of a first-order rate process. In order to determine the change of soil and biomass properties with time, i.e., during a tillage event, it is assumed that the time rate of change of each variable affected can be described[2]. This incremental change has the general form:

$$\begin{aligned} \Delta \mathrm{X} &= a(\mathrm{X} - \mathrm{X}_{\mathrm{lim}}) \\ \textit{where}&: \\ a &= a_t \Delta t,\ \text{Proportional coefficient} \\ a_t &= \text{Time coefficient} \\ \Delta t &= \text{Time increment of change} \\ \Delta \mathrm{X} &= \text{Change in X during operation} \\ \mathrm{X} &= \text{Initial value} \\ \mathrm{X}_{\mathrm{lim}} &= \text{Limiting value of X} \end{aligned} \qquad \textbf{(1)}$$

Thus, the change in X during an event is directly proportional to its value at the beginning of the event and perhaps limited by a specified value (i.e., X_{lim}) other than zero. For example, if X were to represent the soil bulk density, then X_{lim} would represent the lower limit for the bulk density.

Because the speeds of individual operations are assumed to be approximately the same (less than the submodel time step of one day), Δt is considered a constant, and, hence, the dimensionless proportional coefficient a rather than the true time coefficient a_t is used. Therefore, it is expected that a will be a function of parameters that may cause ΔX to change, i.e.,

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[2] Or more correctly, the time increment of change, because we must use a finite difference representation in the submodel.

$a = f$ (Tillage Implement, Soil Texture, Soil Moisture, ...)

Soil Surface Manipulation

Soil surface is described within WEPS by random and oriented roughness values, the fraction of the surface that is crusted, and the amount of loose, erodible material on the crusted fraction of the surface. The post operation surface state is determined based upon parameters affecting the following properties:

1. Percent of surface area modified (tilled).

   The fraction of surface tilled by a management operation is assigned to each operation. Primary and secondary tillage operations typically till the entire surface, whereas row cultivation operations may till only the area between crop rows.

2. Fraction of crust destroyed.

   Management operations, such as tillage, that modify the soil surface can destroy crust, if it is present prior to the operation. The amount of the surface crust destroyed by a management operation is specified by the decrusting parameter as defined in Eq. [2]. Most management operations that affect the surface configuration will destroy all of the crust area; however, some operations do not modify (till) the entire surface area. Thus, the decrusting factor is applied only to the fraction of surface being tilled. Also, because the "loose erodible material" is defined only where a developed crust exists, its value is set to zero when the crust fraction is zero.

$$Cr_f = (1-\kappa)\ \zeta\ Cr_o + (1-\zeta)\ Cr_o \tag{2}$$

where:

Cr_f = Fraction of surface crusted after operation

Cr_o = Fraction of surface crusted before operation

κ = Fraction of crust removed $(0 \le \kappa \le 1)$

ζ = Fraction of surface tilled $(0 \le \zeta \le 1)$

3. Random roughness.

   Random roughness of a surface within the MANAGEMENT submodel is represented in terms of the random roughness index of Allmaras et al. (1966). The nominal random roughness value, RR_o, expected from a tillage operation is usually what is obtained under typical field conditions. However, some tillage tools cannot reduce the surface roughness to the value usually associated with the operation under some field surface roughness conditions. Therefore, a tillage intensity factor, λ, also is assigned to each tillage operation as is done in WEPP (Lane and Nearing, 1989). If the pre-tillage random roughness is greater than the nominal random roughness associated with an implement, then the post tillage random roughness value is computed using the tillage intensity factor as shown in Eq. [3]. If the tillage operation does not modify the entire surface, the post tillage random roughness is weighted accordingly.

$$RR_f = \begin{cases} \zeta\, RR_{impl} + (1-\zeta)\, RR_o & RR_{impl} \geq RR_o \\ \zeta\left[\lambda RR_{impl} + (1-\lambda)\, RR_o\right] + (1-\zeta)\, RR_o & RR_{impl} < RR_o \end{cases}$$

where:

RR_f = Final tilled surface random roughness (mm) **(3)**
RR_o = Pre tillage surface random roughness (mm)
RR_{impl} = Assigned nominal RR value for tillage operation (mm)
λ = Tillage intensity factor ($0 \leq \lambda \leq 1$)
ζ = Fraction of surface tilled ($0 \leq \zeta \leq 1$)

4. Oriented roughness.

   Oriented roughness is defined within the submodel as uniform rows of ridges and furrows running in parallel lines. Thus, oriented roughness can be specified via a ridge top width, ridge height, ridge spacing, and row direction (ridge slopes of 4:1 are assumed to exist and ridge top and furrow channel widths are assumed equal). If dikes exist in the furrows, they are assumed to be spaced equally with the same slope and top width as the ridges. Therefore, only dike height and spacing are required to define ridges within the model. Default values for ridge and dike parameters are provided for each tillage operation but are modifiable by the user.

   A "ridge modification" flag also is assigned to each management operation. If the flag value is set to "destroy ridges", it is assumed that the tillage operation being specified can change the current surface configuration into the desired configuration with respect to oriented roughness. If the flag value is "modify ridges", the operation will modify the current oriented roughness and may completely eliminate the original ridges, depending on tillage depth specified. If the flag value is "no effect", then the operation will not disturb the current oriented roughness values.

Soil Mass Manipulation

Soil mass manipulation processes modify a series of stacked, parallel, homogeneous layers with a specified thickness. Conservation of mass is a fundamental principle used in developing the submodel processes that affects the following soil layer properties:

1. Aggregate Size Distribution (ASD)

   The aggregate size distribution at the soil surface provides information necessary to determine the quantity of erodible-size aggregates available for direct emission and saltation, as well as the degree of shelter provided to erodible-size aggregates by larger aggregates. Aggregate size distribution below the surface is also of interest, because emergency tillage operations used to control wind erosion fail if sufficient non-erodible aggregates are not available to bring to the surface.

Aggregate size distributions are represented within WEPS as a 4-parameter modified lognormal distribution (Wagner and Ding, 1994). Tillage-induced aggregate breakage is simulated within the MANAGEMENT submodel of WEPS with a Markov[3] chain-based, two-parameter, stochastic model[4] (Wagner and Ding, 1993), which can be stated as follows in the context of the soil aggregate crushing process:

A soil aggregate is assumed to consist of many particles, with each having an infinitesimal volume and a unit mass. The soil particles can travel only downward from a larger aggregate size class to smaller aggregate size classes after each tillage pass (crushing of an aggregate). If a size class is called a "state", then the transition of soil particles from one state to another can be treated as a completely random event. A probability matrix, $P[i,j]$, can be constructed for all possible transitions occurring in the soil when its aggregate size distribution (mass fractions across different size classes) shifts or transfers from $w[i]$ to $\hat{w}[k]_{(0\ \mathrm{to}\ i-1)}$ size, after one crushing stage (tillage pass). $P[i,j]$, often called a transition matrix, maintains the properties of a Markov chain and does not change with the number of tillage passes performed but depends on the type of tillage and the specific soil conditions.

Mathematically, the Markov chain-based crushing model is of the form:

$$\hat{w}[i]_{(1\times n)} = w[i]_{(1\times n)}\, P[i,j]_{(n\times n)} \tag{4}$$

where:
$\hat{w}[i]$ = post tillage array of aggregate size class fractions
$w[i]$ = pre tillage array of aggregate size class fractions
$P[i,j]$ = transition matrix
i,j = indices for soil aggregate size classes
n = maximum number of aggregate size classes

The effectiveness of the model relies on how accurately the transition matrix, P[i,j], can be estimated. Because estimating each element of the transition matrix (transition probability, p_{ij}) individually is almost impossible, it is assumed that the p_{ij} follows a binomial distribution[5] as shown in Eq.[5]. The binomial distribution

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[3] A Markov process is one in which the next "state" is dependent only on the present "state" and is independent of any previous "state".

[4] A stochastic model is one having at least one component that will be treated as exhibiting random behavior.

[5] This is the probability distribution of Bernoulli trials, which are repeated independent trials. Each trial has two possible outcomes, and the corresponding probability remains the same for all trials.

is a typical discrete probability distribution function.

$$p_{ij} = \begin{pmatrix} i-1 \\ j-1 \end{pmatrix} p_i^{j-1} (1-p_i)^{i-j} \qquad i = 1,2,...,n \ , \quad j = 1,2,.....,i \tag{5}$$

In Eq.[5], p_i is defined as the *probability function of breakage*, which has a value within the interval [0,1] and generally can be expressed as an algebraic function of sieve size, x_i, and a number of parameters, a_1, a_2,...,a_m.

$$p_i = f(x_i, a_1, a_2, ..., a_m) \tag{6}$$

The probability function of breakage, p_i, reflects how much breaking is occurring in the aggregate size class *i*. A large p_i indicates a small percentage of soil aggregates of size class *i* that are breaking into smaller size classes. If $p_i = 1$, then no aggregates of size class *i* are being broken down, and if $p_i = 0$, then all of the aggregates in size class *i* are being broken down into smaller size classes.

It is presumed that p_i is related to the tillage tool, tillage speed, tillage depth, soil conditions, and sieve cut sizes used in measuring $w[i]$ and $\hat{w}[i]$. Therefore, the a_i parameters in Eq.[6] are expected to be functions of those conditions. The most suitable two-parameter functional representation for p_i was found to be:

$$p_i = \frac{1.0}{1.0 + \exp\left(-\alpha + \beta \dfrac{gmd_i}{gmd_{\max}} \right)} \tag{7}$$

where[6]:

i = 1, 2, 3, ..., n, n+1 (n = number of sieve cuts)
gmd_i = geometric mean dia. of aggregates in size class *i* (x_{i-1} to x_i)
gmd_{max} = geometric mean dia. of aggregates in largest size class (x_n to x_{n+1})

Parameter α reflects the breakage of all soil aggregates regardless of size. As α decreases, the percentage of soil aggregates breaking increases. Parameter ß reflects the unevenness of breakage among aggregates in different size classes. Large ß values indicate that crushing mainly affects the large soil aggregates.

Tillage-induced aggregate breakage and, thus, the crushing parameters are dependent upon soil type and water content at time of tillage (Wagner, Ambe, and

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[6] For a rotary sieve of *n* sieves, the x_0 and x_{n+1} are arbitrary minimum and maximum aggregate sizes assumed to exist in the data. The values used during model development analysis were 0.01 mm and 152.4 mm, respectively. These values also correspond to the x_o and x_∞ values from a four-parameter "modified" lognormal function describing an aggregate size distribution.

Barnes, 1992; Wagner and Ding, 1993, Wagner, Ambe, and Ding, 1994), but determination of those functional relationships is still being pursued.

2. Mixing among soil layers

   The mixing process represents the uniting or blending of soil layer properties within soil layers only. The burial of surface constituents such as crop residue and fertilizer below the surface is not represented by this mixing process but rather the burial process described later.

   The mixing process employed in the MANAGEMENT submodel uses a single mixing parameter. The values range from zero for no mixing to 1 for complete mixing. All layers within the tillage zone are weighted equally in the layer mixing process. Eq.[8] describes the mass mixing process, which is similar to the volume-based mixing process used in the EPIC and WEPP models (Sharpley and Williams, 1990; Lane and Nearing 1989).

$$\hat{X}_l = (1-\mu)X_l + \mu\left(\frac{\sum_{k=1}^{m}(\rho_k \Delta Z_k X_k)}{\sum_{k=1}^{m}(\rho_k \Delta Z_k)}\right) \tag{8}$$

where:

$\hat{X}_l$ = Final mass concentration in layer l

X_l, X_k = Initial mass concentrations in layers l and k

μ = Mass mixing efficiency coefficient

$\rho_k \Delta Z_k$ = Mass of soil in layer k

l,k = Soil layer indices

m = Maximum number of soil layers

   All soil layer variables defined as concentrations of the soil mass in the layer, e.g., intrinsic soil properties such as the fractions of sand, silt, clay, and organic matter; cation exchange capacity; and nutrient levels can be mixed directly using Eq. [8].

3. Loosening

   The loosening process is defined as the addition of air into the soil layer. This is represented as a change in the soil layer bulk density in the MANAGEMENT submodel by Eq. [9]. as defined in the EPIC model (Sharpley and Williams, 1990). The "settled" bulk density, ρ_s, is determined using an interpolation of published soil texture triangle values (Rawls, 1983). Applying the conservation of mass principle requires a corresponding change to the soil layer thickness as shown in Eq. [10].

$$\hat{\rho}_l = \rho_l - (\rho_l - \frac{2}{3}\rho_{s\,l})\,\mu$$

where:

$\hat{\rho}_l$ = Post tillage bulk density for layer l **(9)**
ρ_l = Pre tillage bulk density for layer l
$\rho_{s\,l}$ = Settled bulk density for layer l
μ = Mass mixing efficiency coefficient

$$\Delta\hat{Z}_l = \Delta Z_l \frac{\rho_l}{\hat{\rho}_l}$$

where:

$\Delta\hat{Z}_l$ = Post tillage layer thickness for layer l **(10)**
ΔZ_l = Pre tillage layer thickness for layer l
$\hat{\rho}_l$ = Post tillage bulk density for layer l
ρ_l = Pre tillage bulk density for layer l

4. Invert

   The inversion process is the reversal of the vertical order of soil layers within the working depth of the tillage tool. Thus, inversion is simply the reordering of the soil layers in the model and reassigning layer thicknesses based on the layer thickness constraints imposed by WEPS. Because the new layer boundaries are not likely to match the original boundaries, the original layer properties are repartitioned into the new layers.

Biomass Manipulation

The biomass manipulation processes describe the effects that management operations have on the growing crop and the various biomass pools maintained in the WEPS model. The biomass manipulation processes handled by the MANAGEMENT submodel are:

1. Bury/Lift

   Transferring aboveground biomass into the soil or the inverse process of bringing buried biomass to the surface. This process occurs with many tillage operations.

2. Cut

   Cutting standing biomass to a prescribed height. The biomass above the "cut" height will be either removed or added to the surface biomass pool.

3. Flatten

   Moving a portion of the standing biomass to the soil surface. The process is usually the result of an operation that flattens standing residue (Wagner and Nelson, 1995).

4. Kill

   Stopping the growth of biomass. The process may be initiated by tillage operations, the application of herbicides, or burning.

5. Remove

   Removing biomass from the site. This process is usually the result of harvest, grazing, or burning operations.

Soil Amendments

Addition of specific materials to the soil and/or surface also are addressed in the MANAGEMENT submodel. Currently, fertilizers (nitrogen and phosphorous), irrigation water, and biomass can be applied to the surface or incorporated into the soil. The quantity of amendments applied are user-specified for those operations. The process of applying seeds to the surface and/or soil is also present in the sense that it triggers the CROP submodel to begin simulating the growth of a new crop.

MANAGEMENT Submodel Assumptions and Limitations

Several assumptions and limitations have been imposed on the MANAGEMENT submodel. The reasons vary from simply limiting the scope of the submodel to inadequate knowledge of specific processes that may have a significant impact on the soil and/or surface condition. Here is the list of current assumptions and limitations that impact the MANAGEMENT submodel.

1. Total soil water content within the current tillage zone is assumed to be unaffected by a tillage operation within the MANAGEMENT submodel. The HYDROLOGY submodel is expected to handle changes in surface water content and, therefore, appropriately represent the usual rapid drying of the surface layer following tillage.

2. Tillage speed is not included as an independent variable affecting how a tillage operation modifies the soil and surface within the submodel. However, each tillage operation is assigned a tillage speed upon which the effects on the soil and surface are based (the soil surface, mass, and biomass manipulation parameters).

3. Tillage depth is assumed to not influence how a tillage operation affects the soil and surface, except for determining which soil layers are affected directly by a tillage operation.

4. Effects of tillage operations on soil layers below the tillage depth are currently not considered, e.g., subsoil compaction. These will be addressed in a future release of the MANAGEMENT submodel.

5. The effects of a management operation are assumed to be homogeneous within a subregion. Effects from tractor tires will not be considered. Certain zone-related tillage operations, such as row cultivation, are treated in a manner such that the result will be "averaged" and "equivalent" values will represent the homogeneous region.

6. Emergency tillage for wind erosion prevention or control and strip cropping practices are considered in WEPS by specifying multiple, separate, noncontiguous, homogeneous subregions.

7. Default ridge and dike geometric specifications (oriented roughness) can be changed by the user. If the tillage depth specified is not sufficient to create or destroy them (for a particular tillage operation that does so), the MANAGEMENT submodel will modify the tillage depth accordingly to obtain the desired ridge and/or dike specifications. Tillage operations that do not modify the current ridge and/or dike specifications will not do so (i.e., ridge tillage).

8. Soil tillage depths are adjusted to the nearest soil layer boundary specified within WEPS. This ensures that the most recent tillage operation modifications on the soil "state" are represented adequately.

9. Aggregate stability and aggregate density are assumed to be unaffected by tillage operations. However, these values of properties may change among soil layers within the tillage zone because of aggregate mixing among layers caused by tillage operations.

Summary

The WEPS MANAGEMENT submodel attempts to simulate the major processes related to the most prevalent cultural practices used by producers and land managers that influence a site’s susceptibility to wind erosion. The range of practices includes primary and secondary tillage, cultivation, planting/seeding, harvesting, and fertilization operations, as well as irrigation, burning, and grazing. The processes are simulated via a physical basis if possible, incorporating conservation of mass and energy concepts. Because use of a minimum number of parameters with readily available and/or attainable values was a goal of submodel design, simplifications were made in representing some processes. Simulation of other processes was constrained simply by a lack of knowledge about those processes. However, because of its design, the WEPS MANAGEMENT submodel, can be expanded and improved as new knowledge is gained relating to the physical processes affecting the soil surface, mass, and biomass.

List of Symbols

Symbol	Definition	Unit
f	generic function	dimensionless
a	dummy proportional coefficient	dimensionless
a_t	dummy time coefficient	s^{-1}
Δt	time increment of change	s
X	dummy variable	dimensionless
Cr	fraction of surface consisting of crust	$m^2\ m^{-2}$
κ	fraction of surface crust destroyed in tilled region	$m^2\ m^{-2}$
ζ	fraction of surface area tilled by operation	$m^2\ m^{-2}$
RR	random roughness	mm
λ	tillage intensity factor	dimensionless
x	aggregate size	mm
$w[i]$	array of aggregate size class mass fractions	dimensionless
$P[i,j]$	probability transition matrix	dimensionless
p_{ij}	transition probability	dimensionless
p_i	probability function of breakage	dimensionless
gmd_i	geometric mean diameter of aggregate size class	mm
ρ	soil layer bulk density	$Mg\ m^{-3}$
ΔZ	soil layer thickness	mm
μ	mixing coefficient	$kg\ kg^{-1}$
ρ_s	settled bulk density	$Mg\ m^{-3}$
Subscripts		
f	final value	
i	index for the soil aggregate size classes	
j	index for the soil aggregate size classes	

Symbol	Definition	Unit
k	dummy summation index	
l	index for the soil layers	
m	maximum number of soil layers	
n	maximum number of aggregate size classes	
o	initial value	
Superscripts and other symbols		
Δ	change in symbol value	
^	final value of the capped symbol	

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