5 Assessments of Soil Erosion and Crop Productivity with Process Models (EPIC)

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Accurate estimates of future soil productivity are essential in agricultural decision making and planning from the field scale to the national level. Soil erosion depletes soil productivity, but the relationship between erosion and productivity is not well defined. Until the relationship is adequately developed, selecting management strategies that maximize long-term crop production will be impossible.

The Soil and Water Resources Conservation Act of 1977 (RCA) requires a report by 1985 that establishes the current status of soil and water resources in the USA. One important aspect of these resources is the effect of erosion on long-term soil productivity. The National Soil Erosion—Soil Productivity Research Planning Committee documented what is known about the problem, identified what additional knowledge is needed, and outlined a research approach for solving the problem (Williams et al., 1981). One of the most urgent and important needs outlined in the research approach was the development of a mathematical model for simulating erosion, crop production, and related processes. This model will be used to determine the relationship between erosion and productivity for the USA. Thus, a national ARS erosion-productivity modeling team was organized and began developing the model during 1981. This team consisted of J. R.

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Williams, M. J. Shaffer, K. G. Renard, G. R. Foster, J. M. Laflen, L. Lyles, C. A. Onstad, A. N. Sharpley, A. D. Nicks, C. A. Jones, C. W. Richardson, P. T. Dyke, K. R. Cooley, and S. J. Smith. The model, called Erosion-Productivity Impact Calculator (EPIC), is composed of physically based components for simulating erosion, plant growth, and related processes and economic components for assessing the cost of erosion, determining optimal management strategies, etc.

Simultaneously and realistically, EPIC simulates the physical processes involved, using readily available inputs. Commonly used EPIC input data (weather, crop, tillage, and soil parameters) are available from a computer filing system assembled especially for applying EPIC throughout the USA. The model requires detailed soils information obtained from the SCS pedon descriptions of chemical and physical properties. The SCS Soils-5 database can be used by applying techniques for estimating missing data, although simulation accuracy is reduced.

Since erosion can be relatively slow, EPIC can simulate hundreds of years if necessary. EPIC is generally applicable, computationally efficient (operates on a daily time step), and capable of computing the effects of management changes on outputs. The model must be comprehensive to define adequately the erosion-productivity relationship.

Outputs from EPIC (crop inputs, costs, erosion rates, etc.) will be entered in the Center for Agricultural and Rural Development (CARD) linear programming model (Meister and Nicol, 1975) to accomplish the national RCA analysis.

The components of EPIC can be placed into eight major divisions for discussion—hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, and economics. A detailed description of the EPIC model was given by Williams et al. (1982). An abbreviated description of the components of the EPIC model and results of model testing are presented here.

5-1 MODEL DESCRIPTION

Although EPIC is a fairly comprehensive model, it was developed specifically for application to the erosion-productivity problem. Thus, user convenience was an important consideration in designing the model. The computer program contains 53 subroutines but only 2700 FORTRAN statements. Since EPIC operates on a daily time step, computer cost for overnight turnaround is only about $0.15 per year of simulation on an AMDAHL 470 computer. The model can be run on a variety of computers, since storage requirements are only 210 kilobytes.

The drainage area considered by EPIC is generally small (ca. 1 ha) because soils and management are assumed to be spatially homogeneous. In the vertical direction, however, the model can work with any variation in soil properties. The soil profile is divided into a maximum of 10 layers (the top layer thickness is set at 10 mm and all other layers may have variable thickness). When erosion occurs, the second-layer thickness is reduced by the amount of the eroded thickness, and the top-layer properties are adjusted by interpolation (according to how far the top layer moves into the second layer). When the second-layer thickness becomes zero, the top layer starts moving into the third layer, etc.

Following are descriptions of EPIC's components and the mathematic relationships used to simulate the processes involved.

5-1.1 Hydrology

5-1.1.1 Surface Runoff

5-1.1.1.1. Surface runoff is predicted for daily rainfall using the SCS curve number equation (USDA-SCS, 1972):

$$Q = (R - 0.2s)^2/R + 0.8s \quad [1]$$

where Q is the daily runoff, R is the daily rainfall, and s is a retention parameter. The retention parameter s is related to soil water content with the equation

$$s = s_{mx}(UL - SW)/UL \quad [2]$$

where SW is the soil water content in the root zone minus the 15-bar water content, UL is the upper limit of soil water storage in the root zone (porosity minus 15-bar water content), and s_{mx} is the maximum value of s. Thus, the retention parameter s ranges from s_{mx}, the I (dry) moisture condition curve number, to zero. A depth weighting technique is used to express the effect of the soil water distribution on the retention parameter.

The EPIC model for simulating surface runoff is similar to option one of the CREAMS runoff model (Knisel, 1980; Williams and Nicks, 1982). The only difference is that EPIC accommodates variable soil layers. In addition to the CREAMS surface runoff component, EPIC includes a provision for estimating runoff from frozen soil. If the temperature in the second soil layer is less than 0°C, the curve number is assigned a value of 98 regardless of the soil water content.

5-1.1.1.2 Peak Runoff Rate. Peak runoff rate predictions are based on a modification of the rational formula:

$$q_p = (\alpha)(Q)(A)/360(t_c) \quad [3]$$

where q_p is the peak runoff rate in m^3/s, α is a dimensionless parameter that expresses the proportion of total rainfall that occurs during the watershed time of concentration (t_c in h), and A is the watershed area in ha.

The time of concentration can be estimated by adding the surface and channel flow times:

$$t_c = t_{cc} + t_{cs} \qquad [4]$$

where t_{cc} is the time of concentration for channel flow and t_{cs} is the time of concentration for surface flow. The t_{cc} can be computed using the equation

$$t_{cc} = \frac{1.1\,(L)\,(n)^{0.75}}{(A)^{0.125}\,(\sigma)^{0.375}} \qquad [5]$$

where L is the channel length from the most distant point to the watershed outlet in km, n is Manning's roughness factor, and σ is the average channel slope. The equation for computing t_{cs} is

$$t_{cs} = \frac{(\lambda \bullet n)^{0.6}}{18\,(S)^{0.3}} \qquad [6]$$

where λ is the surface slope length in m and S is the land surface slope in m/m.

Since the water erosion component of EPIC estimates the maximum 0.5-h amount of each daily rainfall, these estimates are used in calculating α. Besides the convenience of avoiding double calculation, it is important to assure that $\alpha 0._5$ and α are closely related for each storm. The relationship between $\alpha_{0.5}$ and α can be obtained from Hershfield (1961) by fitting a log function to the 10-year frequency rainfall distribution:

$$R_t = R_6\,(t/6)^b \qquad [7]$$

where b is a parameter used to fit the TP-40 relationship at any location, R_t is the rainfall amount for any time t, and R_6 is the 6-h rainfall amount. The value of α is computed with the equation

$$\alpha = \alpha_{0.5}\,(R_{t_c}/R_{0.5}) \qquad [8]$$

Details of the procedure for estimating $\alpha_{0.5}$ are presented in section 5–1.3.1.

5–1.1.2 Percolation

The percolation component of EPIC uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer in the root zone. Once water percolates below the root zone, it is lost from the watershed (becomes groundwater or appears as return flow in downstream basins). Percolation is computed using the equation

$$0 = SW_0\,[1 - \exp(-\Delta t/TT)] \qquad [9]$$

where 0 is the percolation rate in mm/d, SW_0 is the soil water content at the beginning of the day in mm, Δt is the travel interval (24 h), and TT is the travel time through a soil layer in h.

The travel time, TT, is computed for each soil layer with the linear storage equation

$$TT_i = (SW_i - FC_i)/H_i \tag{10}$$

where H_i is the hydraulic conductivity in mm/h and FC is the field-capacity water content in mm. The hydraulic conductivity varies from the saturated conductivity value at saturation to near zero at field capacity:

$$H_i = SC_i\,(SW_i/UL_i)^{\beta_i} \tag{11}$$

where SC_i is the saturated conductivity for layer i in mm/h and β is a parameter that causes H_i to approach zero as SW_i approaches FC_i.

The saturated conductivity is estimated for each soil layer using the equation

$$SC_i = \frac{12.7\,(100 - CLA)}{100 - CLA + \exp[11.45 - 0.097(100 - CLA)]} + 0.25 \tag{12}$$

where CLA is the percentage of clay in the soil layer.

If the layer immediately below the layer being considered is saturated, no flow can occur regardless of the results from Eq. [9]. The effect of lower-layer water content is expressed in the equation

$$0_{ci} = 0_i\sqrt{1 - SW_{i+1}/UL_{i+1}} \tag{13}$$

where 0_{ci} is the percolation rate for layer i in mm/d corrected for the water content in layer i + 1 and o_i is the percolation computed with Eq. [9].

The crack-flow model allows percolation of infiltrated rainfall even though the water content of the soil is less than field capacity. When the soil is dry and cracked, infiltrated rainfall can flow through the cracks of a layer without becoming part of the layer's soil water. However, the portion that does become part of a layer's stored water cannot percolate until the water content exceeds field capacity.

Crack flow is simulated with relationships similar to those used to estimate percolation above field capacity. The amount of percolate caused by crack flow is estimated with the equation

$$O_i = O_{i-1}\,[1 - \exp(-\Delta t/TT_{ci})] \tag{14}$$

where O_{i-1} is the flow from the layer above in mm/d (R − Q for the top layer) and TT_{ci} is the crack-flow travel time in h. Crack-flow travel time is estimated with the equation

$$TT_{ci} = o_{i-1}/(\zeta_i)\,(SC_i) \tag{15}$$

where ζ_i is a dimensionless soil parameter with values from 0 to 1 that expresses degree of cracking.

Percolation is also affected by soil temperature. If the temperature in a particular layer is 0°C or below, no percolation is allowed from that layer. Water can, however, percolate into the layer as dictated by Eqs. [9] and [14].

Since the one-day time interval is relatively long for routing flow through soils, it is desirable to divide the water into several parts for routing. This is necessary because the flow rates are dependent on the soil water content which is continuously changing. For example, if the soil was extremely wet, Eqs. [9], [10], and [11] might greatly overestimate percolation if only one routing was performed using the entire amount ($SW_i - FC_i$). To overcome this problem, EPIC divides each layer's inflow into 4-mm slugs for routing. Also, by dividing the inflow into 4-mm slugs and routing each slug individually through all layers, the lower-layer water-content relationship (Eq. [13]) is allowed to function.

5-1.1.3 Lateral Subsurface Flow

Lateral subsurface flow is calculated simultaneously with percolation. Each 4-mm slug is first given the opportunity to percolate and then the remainder is subjected to the lateral-flow function. Thus, lateral flow can occur when the soil water in any layer exceeds field capacity after percolation. The lateral-flow function (similar to Eq. [9]) is expressed in the equation

$$QR_i = (SW_i - FC_i)\,[1 - \exp(-\Delta t/TT_{Ri})] \qquad [16]$$

where QR_i is the lateral flow rate for soil layer i in mm/d and TT_{Ri} is the lateral-flow travel time in d (time required for subsurface flow to travel a distance equal to the land surface slope length λ).

The lateral-flow travel time is estimated for each soil layer using the equation

$$TT_{Ri} = \frac{1000\,CLA}{CLA + \exp(10.047 - 0.148\,CLA)} \qquad [17]$$

5-1.1.4 Drainage

Underground drainage systems are treated as a modification of the natural, lateral subsurface flow of the area. A drainage system is simulated by simply indicating which soil layer contains the drainage system. EPIC assigns a short travel time of one day to that layer. Since travel time depends on the soil properties and the drain spacing, the drainage travel time may require adjustment for certain applications.

5-1.1.5 Evapotranspiration

The evapotranspiration component of EPIC is Ritchie's ET model (Ritchie, 1972). To compute potential evaporation, the model uses the equation

$$E_0 = 1.28\,(h_0)(\gamma) \qquad [18]$$

where E_0 is the potential evaporation rate in mm/d, h_0 is the net solar radiation, and γ is a psychometric constant. The value of h_0 is calculated with the equation

$$h_0 = (RA)\,(1 - AB)/2.44 \times 10^6 \qquad [19]$$

where RA is the daily solar radiation in J/m^2 and AB is the albedo. The albedo is evaluated by considering the soil, crop, and snow cover. If a snow cover exists with 5 mm or greater water content, the value of albedo is set to 0.8. If the snow cover is less than 5 mm and no crop is growing, the soil albedo is the appropriate value. When crops are growing, albedo is determined using the equation

$$AB = 0.23\,(1.0 - EA) + (AB_S)\,(EA) \qquad [20]$$

where AB_S is the soil albedo, 0.23 is the albedo for plants, and EA is a soil-cover index. The value of EA ranges from 0 to 1.0 according to the equation

$$EA = \exp[-2.9 \times 10^{-5}\,(CV)] \qquad [21]$$

where CV is the sum of above-ground biomass and crop residue in kg/ha.

The value of γ in Eq. [18] can be obtained from the equation

$$\gamma = \delta/\delta + 0.68 \qquad [22]$$

where δ is the slope of the saturation vapor-pressure curve at the mean air temperature. The expression for evaluating δ is

$$\delta = 5304/T_K^2 \exp(21.255 - 5304/T_K) \qquad [23]$$

where T_K is the daily average air temperature in K.

The model computes soil and plant evaporation separately. Potential soil evaporation is predicted with the equation

$$E_{so} = E_0 \exp(-0.4\,LAI) \qquad [24]$$

where E_{so} is the potential evaporation rate at the soil surface in mm/d and LAI is the leaf-area index defined as the area of plant leaves relative to the soil surface area. Actual soil evaporation is computed in two stages. In the first stage, soil evaporation is limited only by the energy available at the surface and, thus, is equal to the potential soil evaporation. When the accumulated soil evaporation exceeds the stage-one upper limit (6 mm), the stage-two evaporative process begins. Stage-two soil evaporation is predicted with the equation

$$E_s = 3.5\,[t^{1/2} - (t - 1)^{1/2}] \qquad [25]$$

where E_s is the soil evaporation rate for day t in mm/d and t is the number of days since stage-two evaporation began.

Plant evaporation is computed with the equations

$$E_p = (E_o)(LAI)/3, \qquad 0 \leq LAI \leq 3 \qquad [26]$$

and

$$E_p = E_o - E_s, \qquad LAI > 3 \qquad [27]$$

where E_p is the predicted plant evaporation rate in mm/d. If soil water is limited, plant evaporation will be reduced as described in section 5–1.6.

5–1.1.6 Irrigation

The EPIC user can simulate either dryland or irrigated agricultural areas. If irrigation is indicated, he must also specify the irrigation efficiency, a plant water-stress level to start irrigation, and whether water is applied by sprinkler or down the furrows. The plant water-stress factor ranges from 0 to 1.0 (1 means no stress and 0 means no growth). These stress factors are described in section 5–1.6. When the user-specified stress level is reached, enough water is applied to bring the root zone up to field capacity, plus enough to satisfy the amount lost if the application efficiency is less than one. The excess water applied to satisfy the specified efficiency becomes runoff and provides energy for erosion.

5–1.1.7 Snow Melt

The EPIC snow-melt component is similar to that of the CREAMS model (Knisel, 1980). If snow is present, it is melted on days when the maximum temperature exceeds 0°C using the equations

$$SML = 4.57\,T_{mx}, \qquad SML < SNO \qquad [28]$$

and

$$SML = SNO, \qquad SML \geq SNO \qquad [29]$$

where SML is the snow melt rate in mm/d, T_{mx} is the daily maximum temperature in °C, and SNO is the water content of snow in mm before melt occurs. Melted snow is treated the same as rainfall for estimating runoff, percolation, etc.

5-1.2 Weather

The weather variables necessary for driving the EPIC model are precipitation, air temperature, solar radiation, and wind. If daily precipitation, air temperature, and solar radiation data are available, they can be input directly to EPIC. Rainfall and temperature data are available for many areas of the USA, but solar radiation and wind data are scarce. Even rainfall and temperature data are generally not adequate for the long-term EPIC simulations of 50 years or more. Thus, EPIC provides options for simulating temperature and radiation, given daily rainfall, or for simulating rainfall as well as temperature and radiation. If wind erosion is to be estimated, daily wind velocity and direction are simulated. (There is no option for inputing wind velocity and direction.) Following are descriptions of the models used for simulating precipitation, temperature, radiation, and wind.

5-1.2.1 Precipitation

The EPIC precipitation model developed by Nicks (1974) is a first-order, Markov chain model. Thus, the model must be provided with monthly probabilities of receiving precipitation if the previous day was dry and monthly probabilities of receiving precipitation if the previous day was wet. Given the initial wet-dry state, the model determines stochastically if precipitation occurs or not.

When precipitation occurs, the amount is determined by generating from a skewed, normal, daily-precipitation distribution. Inputs necessary to describe the skewed normal distribution for each month are the mean, standard deviation, and skew coefficient for daily precipitation. The amount of daily precipitation is partitioned between rainfall and snowfall using average daily air temperature. If the average daily air temperature is 0°C or below, the precipitation is snowfall; otherwise, it is rainfall.

5-1.2.2 Air Temperature and Solar Radiation

The model developed by Richardson (1981) was selected for use in EPIC because it simulates temperature and radiation that correlate properly with one another and with rainfall. The residuals of daily maximum and minimum temperature and solar radiation are generated from a multivariate normal distribution. The means and coefficients of variation for each variable must be input. Since rainfall affects most of the variables, the means and coefficients of variation must be input separately for wet and dry days. Fortunately, a simple cosine function with two parameters adequately fits both the means and coefficients of variation.

The multivariate generation model used implies that the residuals of maximum temperature, minimum temperature, and solar radiation are normally distributed and that the serial correlation of each variable may be described by a first-order linear autoregressive model. Details of the multivariate generation model were described by Richardson (1981). The dependence structure of daily maximum and minimum temperatures and solar radiation was described by Richardson (1982a).

5-1.2.3 Wind

Richardson (1982b) developed the wind simulation model for use with EPIC. The two wind variables considered are average daily velocity and daily direction. Average daily wind velocity is generated from a two-parameter gamma distribution of the dimensionless form

$$U = (V/V_p)^{\eta - 1} \exp[(\eta - 1)(1 - V/V_p)] \qquad [30]$$

where U is a dimensionless variable (0 to 1) expressing frequency of occurrence of wind velocity V in m/s, V_p is the wind velocity at the peak frequency, and η is the gamma-distribution shape parameter. The shape parameter is calculated with the equation

$$\eta = \overline{V}^2/SDV^2 \qquad [31]$$

where $\overline{V}$ is the annual average wind velocity in m/s and SDV is the standard deviation of daily wind velocity in m/s.

Values for the average annual wind velocity and the standard deviation of hourly wind are provided by the Climatic Atlas of the United States (U.S. Department of Commerce, 1968). By experimenting with standard deviations of hourly and daily wind, a correction factor of 0.7 was found to be appropriate for converting hourly to daily standard deviations. The base of the dimensionless gamma distribution (maximum V/V_p) can be determined using Newton's classical method of solving nonlinear equations. The objective function is to select the base to minimize the sum of ln(U) and 11.5. The value of V_p can be determined by differentiating the gamma function expressed in terms of V and setting the result equal to zero:

$$V_p = V_i(\eta - 1)/\eta \qquad [32]$$

where V_i is the mean daily wind velocity for month i. The rejection technique is used to generate a daily value of V/V_p. The daily wind velocity is then computed using the equation

$$V_j = (V_{pi})(V/V_p) \qquad [33]$$

where V_j is the generated velocity for day j, V_{pi} is the peak velocity for month i, and V/V_p is the generated value using the rejection technique.

Wind direction, expressed as radians from north in a clockwise direction, is generated from an empirical distribution specific for each location. The empirical distribution is simply the cumulative probability distribution of wind direction. The Climatic Atlas of the United States (U.S. Department of Commerce, 1968) gives monthly percentages of wind from each of 16 directions. Thus, to estimate wind direction for any day, the model draws a uniformly distributed random number and locates its position on the appropriate monthly cumulative probability distribution.

5-1.3 Erosion

5-1.3.1 Water Erosion

5-1.3.1.1 Rainfall. The water erosion component of EPIC uses the universal soil loss equation (USLE) (Wischmeier and Smith, 1978) as modified by Onstad and Foster (1975). The energy factor in the Onstad-Foster equation is composed of both rainfall and runoff variables. In contrast, the USLE energy factor contains only rainfall variables. The Onstad-Foster equation is

$$Y = [0.646\,EI + 0.45(Q)(q_p)^{0.333}](K)(CE)(PE)(LS), \qquad Q > 0 \quad [34]$$

$$Y = 0 \qquad Q \leq 0$$

where
Y is the sediment yield in t/ha,
EI is the rainfall energy factor in metric units,
Q is the runoff volume in mm,
q_p is the peak runoff rate in mm/h,
K is the soil erodibility factor,
CE is the crop management factor,
PE is the erosion control practice factor, and
LS is the slope length and steepness factor.

The value of K depends on the soil type and is assigned before the simulation begins. Similarly, the PE value is determined initially by considering the conservation practices to be applied. The value of LS is calculated with the equation (Wischmeier and Smith, 1978):

$$LS = (\lambda/22.1)^{\xi}(65.41\,S^2 + 4.56\,S + 0.065) \qquad [35]$$

where S is the land surface slope in m/m, λ is the slope length in m, and ξ is a parameter dependent on slope. To evaluate ξ, EPIC uses the equation

$$\xi = 0.6\,[1 - \exp(-35.835\,S)] \qquad [36]$$

The crop-management factor is evaluated for all days when runoff occurs, using the equation

$$CE = (0.8 - CE_{mn,j})\exp(-0.00115\,CV) + CE_{mn,j} \qquad [37]$$

where $CE_{mn,j}$ is the minimum value of the crop management factor for crop j and CV is the sum of above-ground biomass and surface residue.

The hydrology model supplies estimates of Q and q_p. To estimate the daily rainfall energy in the absence of time-distributed rainfall, one assumes that the rainfall rate is exponentially distributed. The exponential distribution allows easy substitution into and integration of the USLE energy equation for computing daily rainfall energy:

$$EI = \frac{R\,[12.1 + 8.9\,(\log r_p - 0.434)]\,(r_{0.5})}{1000} \qquad [38]$$

where R is the daily rainfall amount in mm, r_p is the peak rainfall rate in mm/h, and $r_{0.5}$ is the maximum 0.5-h rainfall intensity. The value of r_p can be obtained by integrating the exponential rainfall distribution. Since rainfall rates vary seasonally, $\alpha_{0.5}$ (the ratio of the maximum 0.5-h rainfall to the total storm rainfall) is evaluated for each month using U.S. Weather Service information (U.S. Department of Commerce, 1968 and 1979). To estimate the mean value of $\alpha_{0.5}$, the mean value of $R_{0.5}$ must be estimated. The value of $R_{0.5}$ can be computed easily if the maximum 0.5-h rainfall amounts are assumed to be exponentially distributed. From the exponential distribution, the expression for the mean maximum 0.5-h rainfall amount is

$$\overline{R}_{0.5,j} = R_{0.5R,j} / -\ln F_j \qquad [39]$$

where $\overline{R}_{0.5,j}$ is the mean maximum 0.5-h rainfall amount, $R_{0.5F,j}$ is the maximum 0.5-h rainfall amount for frequency F, and subscript j refers to the month. The mean $\alpha_{0.5}$ is computed with the equation

$$\alpha_{0.5j} = \overline{R}_{0.5,j} / \overline{R}_j \qquad [40]$$

where $\overline{R}$ is the mean amount of rainfall for each event (average monthly rainfall/average number of days of rainfall) and subscript j refers to the month. Daily values of $\alpha_{0.5}$ are generated from a two-parameter gamma distribution in a similar manner to that described in generating wind velocity (section 5-1.2.3).

5-1.3.1.2 Irrigation. Erosion caused by applying irrigation water in furrows is estimated with the modified universal soil loss equation (MUSLE) (Williams, 1975):

$$Y = 11.8\,(Q \cdot q_p)^{0.56}\,(K)(CE)(PE)(LS) \qquad [41]$$

where CE, the crop management factor, has a constant value of 0.5 The volume of runoff is estimated by considering the irrigation efficiency:

$$Q = AIR\,(1.0 - EIR) \qquad [42]$$

where AIR is the volume of irrigation water applied in mm and EIR is the irrigation efficiency. The peak runoff rate is estimated for each furrow using Manning's equation and assuming that the flow depth is 0.75 of the row height and that the furrow is triangular. If irrigation water is applied to land without furrows, the peak runoff rate is assumed to be 0.00189 m^3/s per m of field width. Erosion caused by sprinkle irrigation is not considered directly. However, erosion is usually greater than from nonirrigated areas because higher soil water content increased runoff.

5-1.3.2 Wind Erosion

The Manhattan, KS, wind-erosion equation (Woodruff and Siddoway, 1965) was modified by Cole et al. (1982) for use in the EPIC model. The original wind erosion equation is

$$WE = f(I, WC, WK, WL, VE) \quad [43]$$

where

WE is the wind erosion in t/ha,
I is the soil erodibility index in t/ha,
WC is the climatic factor,
WK is the soil-ridge roughness factor,
WL is the field length along the prevailing wind direction in m, and
VE is the quantity of vegetative cover expressed as small grain equivalent in kg/ha.

Equation [43] was developed for predicting average annual wind erosion. The main modification to the model was a conversion from annual to daily predictions to interface with EPIC.

Although two of the variables, I and WC, remain constant for each day of a year, the other variables are subject to change from day to day. The ridge roughness is a function of row height and row interval, according to

$$KR = 4\,HR^2/IR \quad [44]$$

where KR is the ridge roughness in mm, HR is the row height in mm, and IR is the row interval in mm. The ridge-roughness factor is a function of ridge roughness as expressed by the equations

$$WK = 1, \qquad KR < 2.27 \quad [45]$$

$$WK = 1.125 - 0.153\ln(KR), \qquad 2.27 \le KR < 89 \quad [46]$$

and

$$WK = 0.336\exp(0.00324\,KR), \qquad KR \ge 89 \quad [47]$$

Field length along the prevailing wind direction is calculated by considering field dimensions, field orientation, and wind direction:

$$WL = \frac{(FL)(FW)}{FL\,|\cos(\pi/2 + \theta - \phi)| + FW\,|\sin(\pi/2 + \theta - \phi)|} \quad [48]$$

where FL is the field length in m, FW is the field width in m, θ is the wind direction clockwise from north in radians, and ϕ is the clockwise angle between field length and north in radians.

The vegetative-cover equivalent factor is simulated daily as a function of standing live biomass, standing dead residue, and flat crop residue.

$$VE = 0.2533\,(g_1 B_{AG} + g_2 SR + g_3 FR)^{1.363} \quad [49]$$

where g_1, g_2, and g_3 are crop-specific coefficients, B_{AG} is the aboveground biomass of a growing crop in kg/ha, SR is the standing residue from the previous crop in kg/ha, and FR is the flat residue in kg/ha. Thus, all variables in Eq. [43] can be evaluated. To determine the wind-erosion estimate, however, requires a special combination of the factors as follows:

$$E2 = (WK)\,(I) \quad [50]$$

$$E3 = (WK)\,(I)\,(WC) \quad [51]$$

$$WL_0 = 1.56 \times 10^6\,(E2)^{-1.26} \exp(-0.00156\,E2) \quad [52]$$

$$WF = E2\,[1 - 0.1218\,(WL/WL_0)^{-0.3829} \exp(-3.33\,WL/WL_0)] \quad [53]$$

$$E4 = (WF^{0.3484} + E3^{0.3484} - E2^{0.3484})^{2.87} \quad [54]$$

$$E5 = \psi_1\,E4^{\psi_2} \quad [55]$$

$$WE = (E5)\,(DE)/(AE) \quad [56]$$

where field lengths greater than WL_0 in m give no reduction in the erosion estimate,
WF is the field length factor,
ψ_1 and ψ_2 are parameters,
DE is the daily wind energy in KWH/m^2, and
AE is the average annual wind energy in KWH/m^2.
The parameters ψ_1 and ψ_2 are functions of the vegetative-cover factor described by the equations

$$\psi_2 = 1 + (8.93 \times 10^{-5}\,VE) + (8.51 \times 10^{-9}\,VE^2) - (1.59 \times 10^{-13}\,VE^3) \quad [57]$$

and

$$\psi_1 = \exp[(-7.59 \times 10^{-4}\,VE) - (4.74 \times 10^{-8}\,VE^2) + (2.95 \times 10^{-13}\,VE^3)] \quad [58]$$

Daily wind energy is estimated with the equation

$$DE = 0.00617\,(V)^{4.35} \exp(-0.0620\,V) \quad [59]$$

where V is the daily average wind velocity in m/s. Average annual wind energy is estimated by integrating the monthly gamma distributions of wind velocity.

$$AE = 30.4 \sum_{j=1}^{12} \frac{\int_{V_L}^{V_u} (DE)_j \, (U)_j \, dV}{\int_{V_L}^{V_u} U_j \, dV} \quad [60]$$

where U is the frequency of occurrence of wind velocity V, V_u is the upper limit of wind velocity, and V_L is the lower limit of erosive wind velocity.

5-1.4 Nutrients

5-1.4.1 Nitrogen

5-1.4.1.1 Nitrate Loss in Surface Runoff. The amount of nitrate (NO_3-N) in runoff is estimated by considering the top soil layer (10 mm) only. The decrease in NO_3-N concentration caused by water flowing through a soil layer can be simulated satisfactorily using an exponential function. The average concentration for a day can be obtained by integrating the exponential function to give the NO_3-N yield and dividing by the volume of water leaving the layer:

$$VNO_3 = WNO_3 \, [1 - \exp(-QT/POR)] \quad [61]$$

$$c_{NO_3} = VNO_3/QT \quad [62]$$

where

WNO_3 is the weight of NO_3-N contained in the soil layer at the start of a day,

QT is the total water lost from the first layer (Q + O + QR),

POR is the porosity of the layer,

VNO_3 is the amount of NO_3-N lost from the first layer, and

c_{NO_3} is the concentration of NO_3-N in the first layer.

Amounts of NO_3-N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water and the concentration from Eq. [62].

5-1.4.1.2 Nitrate Leaching. Leaching and lateral subsurface flow in lower layers are treated with the same approach used in the upper layer, except surface runoff is not considered.

5-1.4.1.2 Nitrate Transport by Soil Evaporation. When water is evaporated from the soil, NO_3-N is moved upward into the top soil layer by mass flow. The equation for estimating this NO_3-N transport is

$$ENO_3 = \sum_{j=2}^{M} (E_S)_j \, (c_{NO_3})_j \quad [63]$$

where ENO_3 is the amount of NO_3-N moved from lower layers to the top layer by soil evaporation E_S, subscript j refers to soil layers, and M is the number of layers contributing to soil evaporation (maximum depth is 300 mm).

5-1.4.1.4 Organic Nitrogen Transport by Sediment. A loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic nitrogen loss. The loading function is

$$YON = 0.001\,(Y)\,(c_{ON})\,(ER) \qquad [64]$$

where YON is the runoff loss of organic nitrogen (N) in kg/hg, c_{ON} is the concentration of organic N in the top soil layer in g/t, Y is the sediment yield in t/ha, and ER is the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that of the soil. Enrichment ratios are logarithmically related to sediment concentration as described by Menzel (Knisel, 1980). A relationship between enrichment ratio and sediment concentration for individual events was developed for EPIC considering upper and lower bounds. The upper bound of the enrichment ratio is the inverse of the sediment-delivery ratio. The lower limit of the enrichment ratio is 1.0—sediment particle size distribution is the same as that of the soil. The logarithmic equation for estimating the enrichment ratio is

$$ER = x_1\, c_s^{x_2} \qquad [65]$$

where c_s is the sediment concentration g/m^3 and x_1 and x_2 are parameters set by the upper and lower limits.

5-1.4.1.5 Denitrification. As one of the microbial processes, denitrification is a function of temperature and water content. The equation used to estimate the denitrification rate is

$$DN = WNO_3\,\{1 - \exp[(CDN)\,(TF_N)\,(C)]\}, \qquad SWF \geq 0.9 \qquad [66]$$

$$DN = 0.0, \qquad SWF < 0.9$$

where DN is the denitrification rate in kg/(ha•d). CDN is the denitrification constant, TF_N is the nutrient temperature factor, SWF is the soil water factor, and C is the percentage of organic carbon content. The temperature factor is expressed by the equation

$$TF_{Nj} = 0.1 + \frac{0.9\,T_j}{T_j + \exp(9.93 - 0.312\,T_j)}, \qquad T_j > 0 \qquad [67]$$

$$TF_{Nj} = 0.0, \qquad T_j \leq 0$$

where T is soil temperature in °C and subscript j refers to the soil layers. The soil-water factor considers total soil water in the equation

$$SWF = (SW + SW_{15})/POR \qquad [68]$$

where SW_{15} is the 15-bar soil-water content in mm.

5-1.4.1.6 Mineralization. The nitrogen mineralization model is a modification of the PAPRAN (Production of annual pastures limited by rainfall and nitrogen) mineralization model (Seligman and van Keulen, 1981). The model considers two sources of mineralization: fresh organic N associated with crop residue and microbial biomass, and the stable organic N associated with the soil humus pool. Mineralization from the pool of fresh organic N is estimated with the equation

$$\mathrm{RMN} = (\mathrm{DCR})\,(\mathrm{FON}) \qquad [69]$$

where RMN is the N mineralization rate for fresh organic N in kg/(ha•d), DCR is the decay-rate constant for the fresh organic N, and FON is the amount of fresh organic N present in kg/ha. The decay-rate constant is a function of the C:N ratio, the C:P ratio, the composition of crop residue, temperature, and soil water:

$$\mathrm{DCR} = (\mathrm{CNP})\,(\mathrm{RC})\,(\mathrm{SWF})\,(\mathrm{TF_N}) \qquad [70]$$

where CNP is a C:N or C:P ratio factor and RC is a residue composition factor. The value of CNP is calculated with the equation

$$\mathrm{CNP} = \min \begin{cases} \exp[-0.693\,(\mathrm{CNR} - 25)]/25 \\ \exp[-0.693\,(\mathrm{CPR} - 200)]/200 \end{cases} \qquad [71]$$

where CNR is the C:N ratio and CPR is the C:P ratio. The value of RC is determined by the stage of residue decomposition.

Mineralization from the pool of stable organic N is estimated for each soil layer with the equation

$$\mathrm{HMN} = (\mathrm{CMN})\,(\mathrm{SWF})\,(\mathrm{TF_N})\,(\mathrm{ON})\,(\mathrm{BD})^2/(\mathrm{BDP})^2 \qquad [72]$$

where HMN is the mineralization rate for the humus pool in kg/(ha•d), CMN is the stable mineralization-rate constant (0.0001), ON is the amount of organic N in the soil layer in kg/ha, BD is the settled bulk density of the soil, and BDP is the current bulk density as affected by tillage.

5-1.4.1.7 Immobilization. Like mineralization, the immobilization model is a modification of the PAPRAN model. Immobilization is a very important process in EPIC because it determines the residue decomposition rate, which has an important effect on erosion. The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms:

$$\mathrm{WIM} = (\mathrm{DCR})\,(\mathrm{FR})\,(0.016 - c_{\mathrm{NFR}}) \qquad [73]$$

where WIM is the N immobilization rate in kg/(ha•d), c_{NFR} is the N concentration in the crop residue in g/g, and 0.016 is the result of assuming that C = 0.4 FR, the C:N ratio of the microbial biomass and their labile products

= 10, and 0.4 of C in the residue is assimilated. Immobilization may be limited by the availability of N or phosphorus (P). If the amount of N available is less than the immobilization predicted by Eq. [73], the decay rate constant is adjusted with the relationship

$$DCR' = 0.95\ WNO_3/FR\ (0.016 - c_{NFR}) \qquad [74]$$

where DCR′ allows 95% use of the available NO_3-N in a soil layer. A similar adjustment is made if P is limiting. The crop residue is reduced using the equation

$$FR = FR_o - (DCR')(FR_o) \qquad [75]$$

where FR_0 and FR are the amounts of residue in a soil layer at the start and end of a day in kg/ha.

5-1.4.1.8 Crop Uptake. Crop use of N is estimated using a supply and demand approach. The daily crop demand for N can be computed using the equation

$$UND_{IDA} = (c_{NB})_{IDA}\,(B)_{IDA} - (c_{NB})_{IDA-1}\,(B)_{IDA-1} \qquad [76]$$

where UND_{IDA} is the N demand of the crop in kg/ha, c_{NB} is the optimal N concentration of the crop, and B is the accumulated biomass in kg/ha. The optimal crop concentration of N is computed as a function of growth stage using the equation

$$c_{NB} = bn_1 + bn_2 \exp(-bn_3\,B_1) \qquad [77]$$

where bn_1, bn_2, and bn_3 are crop parameters expressing N concentration and B_1 is a dimensionless (0 to 1) expression of accumulated thermal time.

Soil supply of N is assumed to be limited to mass flow of NO_3-N to the roots:

$$UNS_{IDA} = \sum_{i=1}^{M} (u_i)_{IDA} \left(\frac{WNO_{3_i}}{SW_i}\right)_{IDA} \qquad [78]$$

where UNS is the amount of N supplied by the soil in kg/ha, u_i is the water use in mm, and subscript i refers to the soil layers. Actual N uptake on IDA is the minimum of UNS and UND.

5-1.4.1.9 Fixation. Fixation of N is important for legumes. The EPIC model estimates fixation by adding atmospheric N to prevent N stress that constrains plant growth. Section 5-1.6 describes the determination of plant stress factors for N, P, water, and temperature. Plant growth is limited by the minimum for the four factors each day. If N is the active constraint, enough atmospheric N is added to the plant to make the N-stress factor equal the next most constraining factor. The amount of N needed is attributed to fixation.

5-1.4.1.10 Rainfall. To estimate the N contribution from rainfall, EPIC uses an average rainfall concentration of N for a location for all storms. The amount of N in rainfall is estimated as the product of rainfall amount and N concentration.

5-1.4.1.11 Fertilizer. The model provides two options for applying fertilizer. With the first option, the user specifies dates, rates, and depths of application of N and P. The second option is more automated—the only input required is a plant-stress parameter. At planting time, the model takes a soil sample and applies up to 15 kg/ha of N fertilizer if needed. The model also applies enough P to bring the concentration of labile P in the top two layers up to the concentration level at the start of the simulation. Additional N fertilizer may be applied during the growing season (at 25% and 50% of maturity). The amount of N applied with each of these two top dressings is determined by predicting the final crop biomass using a relationship derived from Eqs. [109] and [110] (the crop biomass-energy equations):

$$BF = B_j + (BE)(PRA - \sum_{k=1}^{j} RA_K)(0.03)(BFT) \qquad [79]$$

and

$$FN = (c_{NB})(BF) - UN_j - \sum_{i=1}^{M} WNO_{3_i} \qquad [80]$$

where BF is the crop biomass predicted for the end of the growing season in kg/ha, B_j is the accumulated biomass on day j, BE is the crop parameter for converting energy to biomass in kg/ha. PRA is the potential solar radiation for the growing season, BFT is the user-supplied plant stress parameter, FN is the amount of N fertilizer applied in kg/ha, c_{NB} is the plant concentration of N at the end of the growing season, and UN_j is the amount of plant N on day j. The value of BFT ranges from 0.0 to 1.0. Thus, the user can adjust the N fertilizer rate by assuming various stress levels (BFT) in predicting the final biomass. Obviously, before each fertilizer application, the model sums the NO_3-N content of each soil layer using Eq. [80].

5-1.4.2 Phosphorus

5-1.4.2.1 Soluble Phosphorus Loss in Surface Runoff. The EPIC approach is based on the concept of partitioning pesticides into the solution and sediment phases as described by Leonard and Wauchope (Knisel, 1980). Because P is mostly associated with the sediment phase, the equation for soluble P runoff can be expressed in the simple form:

$$YSP = 0.01\,(c_{LP1})(Q)/k_d \qquad [81]$$

where YSP is the soluble P in kg/ha lost in runoff volume Q in mm, c_{LP1} is the concentration of labile P in soil layer 1 in g/t, and k_d is the P concentration in the sediment divided by that of the water in m^3/t. The value of k_d used in EPIC is 175.

5-1.4.2.2 Phosphorus Transport by Sediment. Sediment transport of P is simulated with a loading function as described in organic N transport. The P loading function is

$$YP = 0.001\,(Y)\,(c_p)\,(ER) \qquad [82]$$

where YP is the sediment phase of the P loss in runoff in kg/ha and c_p is the concentration of P in the top soil layer in g/t.

5-1.4.2.3 Mineralization. The P mineralization model developed by Jones et al. (1982) is similar in structure to the N mineralization model. Mineralization from the pool of fresh organic P is estimated for each soil layer with the equation

$$RMP = (DCR)\,(FOP) \qquad [83]$$

where RMP is the mineralization rate of fresh organic P in kg/(ha•d). Mineralization from the pool of stable organic P associated with humus is estimated for each soil layer using the equation

$$HMP = (LF_M)\,(CMN)\,(TF_N)\,(SWF)\,(OP) \qquad [84]$$

where HMP is the mineralization rate of humus P in kg/(ha•d), LF_M is the mineralization factor for labile P, and OP is the organic P content of the soil layer in kg/ha. The mineralization factor for labile P is computed with the equations

$$LF_M = 5 - 0.16\,c_{LP}, \qquad c_{LP} \leq 25 \qquad [85]$$

$$LF_M = 1, \qquad c_{LP} > 25 \qquad [86]$$

Thus, when $c_{LP} > 25$, the mineralization of humus P is directly proportional to the mineralization of humus N. However, because of increasing phosphatase activity of soil microbes, the ratio of P to N mineralization increases when labile P is inadequate.

5-1.4.2.4 Immobilization. The P immobilization model also developed by Jones et al. (1982) is similar in structure to the N immobilization model. The daily amount of immobilization is computed by subtracting the amount of P contained in the crop residue from the amount assimilated by the microorganisms:

$$WIP = (DCR')\,(FR)\,(0.16\,LF_I - c_{PFR}) \qquad [87]$$

where WIP is the P immobilization rate in kg/(ha•d), c_{PFR} is the P concentration in the crop residue, 0.16 is the result of assuming that carbon = 0.4 of fresh crop residue and 0.4 of the carbon in the residue is assimilated by soil microorganisms, LF_I is the immobilization factor by labile P allowing the P:C ratio of soil microorganisms to range from 0.01 to 0.02 as a function of labile P concentration. The immobilization factor for labile P is computed with the equations

$$LF_I = 0.01 + 0.0004\, c_{LP}, \qquad c_{LP} \leq 25 \qquad [88]$$

$$LF_I = 0.02, \qquad c_{LP} > 25 \qquad [89]$$

5-1.4.2.5 Cycling of Mineral Phosphorus. The mineral P model was developed by Jones et al. (1982). Mineral P is transferred among three pools: labile, active mineral, and stable mineral. When P fertilizer is applied, it is labile (available for plant use). However, a fraction is quickly transferred to the active mineral pool according to the equation

$$MPR = 0.1\,(AP)\,(SWF)\exp(0.115\,T - 2.88) \qquad [90]$$

where MPR is the rate of flow from the labile pool (AP) to the active-mineral P pool in kg/(ha•d) for each soil layer. Simultaneously, P flows from the active mineral pool back to the labile pool (usually at a much slower rate) according to the equation

$$LPR = 0.1\,(MP_A)\,(SWF)\exp(0.115\,T - 2.88)\,(PSP/1\text{-}PSP) \qquad [91]$$

where LPR is the flow rate from the active mineral pool to the labile pool in kg/(ha•d), MP_A is the amount in the active-mineral P pool in kg/ha, and PSP is the P-sorption coefficient defined as the fraction of fertilizer P remaining in the labile pool after an initial rapid phase of P sorption is complete. The P-sorption coefficient is a function of chemical and physical soil properties as described by Eq. [92] for calcareous soils and Eq. [93] for non-calcareous soils.

$$PSP = -0.0577 - 0.00380\,CLA + 0.0682\,pH - 0.00198\,CEC - 0.00624\,CAC \qquad [92]$$

$$PSP = -0.0682 - 0.00303\,AP - 0.00482\,CLA + 0.122\,pH - 0.00164\,CLA/C \qquad [93]$$

where PSP is the P-sorption coefficient for each soil layer, pH is the soil pH, CEC is the cation exchange capacity, C is the percentage of organic carbon, and CLA is the percentage of clay content of the layer (Jones et al., 1982). In either case, PSP is constrained within the limits $0.15 \leq PSP \leq$

0.75. Flow between the pools of active and stable mineral P is governed by the equation

$$\text{ASPR} = (\omega)(c_{MPA} - 5) \qquad [94]$$

where ASPR is the flow rate between the pools of active and stable mineral P in kg/(ha•d) for a particular soil layer, ω is the flow coefficient, and c_{MPA} is the concentration of active mineral P in the soil layer in g/t. The flow coefficient, ω, is a function of PSP as expressed (Jones et al., 1982) by Eq. [95] for noncalcareous soils and Eq. [96] for calcareous soils:

$$\omega = \exp(-1.77\,\text{PSP} - 7.05) \qquad [95]$$

$$\omega = 0.00076 \qquad [96]$$

5-1.4.2.6 Crop Uptake. Crop use of P is estimated with the supply and demand approach described in the N model. The daily plant demand is computed with Eq. [76] written in the form

$$\text{UPD}_{\text{IDA}} = (c_{PB})_{\text{IDA}}(B)_{\text{IDA}} - (c_{PB})_{\text{IDA-1}}(B)_{\text{IDA-1}} \qquad [97]$$

where UPD_{IDA} is the P demand for the plant in kg/ha and c_{PB} is the optimal P concentration for the plant. The optimal plant concentration of P is computed with Eq. [77] written in the form

$$c_{PB} = bp_1 + bp_2 \exp(-bp_3\, B_1) \qquad [98]$$

where bp_1, bp_2, and bp_3 are crop parameters expressing P concentration. Plant supply of P is estimated using the equation

$$\text{UPS}_{\text{IDA}} = 1.5\,\text{UPD}_{\text{IDA}} \sum_{i=1}^{M} (\text{SWF})_i (\text{LF}_u)_i (\text{RW}_i/\text{RWT}_{\text{IDA}}) \qquad [99]$$

where UPS is the amount of P supplied by the soil in kg/ha, LF_u is the labile P factor for uptake, RW is the root weight in layer i, and RWT is the total root weight on day IDA in kg/ha. The labile P factor for uptake ranges from 0 to 1 according to the equations

$$\text{LF}_u = (c_{LP} - 0.5)/24.5, \qquad 0.5 \le c_{LP} \le 25 \qquad [100]$$

$$\text{LF}_u = 0.0, \qquad c_{LP} < 0.5 \qquad [101]$$

$$\text{LF}_u = 1.0, \qquad c_{LP} > 25 \qquad [102]$$

As with N, the actual P uptake is the minimum of UPD and UPS.

5-1.5 Soil Temperature

Daily average soil temperature is simulated at the center of each soil layer for use in nutrient cycling and hydrology. The basic soil-temperature equation is

$$T(Z,t) = \bar{T} + \frac{AM}{2} \exp(-Z/DD) \cos \left[\frac{2\pi}{365}(t - 200) - Z/DD\right] \qquad [103]$$

where

Z is depth from the soil surface in mm,
t is time in d,
$\bar{T}$ is the average annual air temperature in °C,
AM is the annual amplitude in daily average temperature in °C, and
DD is the damping depth for the soil in mm.

Equation [103] provides estimates of air temperature ($Z = 0$) as well as soil temperature. Since air temperature is provided by the weather component of EPIC, the soil-temperature model should be capable of using these air temperatures as drivers. Otherwise, Eq. [103] would predict the same temperatures for a given day each year. To allow simulated air temperature to be used as the soil-temperature driver, an equation was developed to estimate soil-surface temperature:

$$TG_{IDA} = (1.0 - AB) \left[\left(\frac{TMX + TMN}{2.0}\right)(1.0 - RA/3.35 \times 10^7) + TMX\, RA/800\right] + (AB)(TG_{IDA-1}) \qquad [104]$$

where

TG is the soil surface temperature in °C,
AB is the surface albedo,
TMX is the maximum daily air temperature in °C,
TMN is the minimum daily air temperature in °C, and
RA is the daily solar radiation in J/m^2.

Besides providing a mechanism for using daily simulated air temperature, Eq. [104] also expresses the effect of solar radiation and cover (a function of AB) on soil temperature. The values of TG on the day of interest and the four days immediately preceding are averaged to adjust Eq. [103]. The adjustment is made by replacing T(0,t) with TG, which is a better estimate of the surface temperature than T(0,t) because current weather conditions are considered. Soil temperature at any depth is also corrected by damping the difference between TG and T(0,t) and adding it to the estimate from Eq. [103]. Thus, the final equation for estimating soil temperature at any depth is

$$T(Z,t) = \bar{T} + \left\{\frac{AM}{2} \cos\left[\frac{2\pi}{365}(t - 200)\right] + TG - T(0,t)\right\} e^{-Z/DD} \qquad [105]$$

The damping depth is a function of soil-bulk density and water content as expressed in the equations

$$DP = 1000 + \frac{2500\ BD}{BD + 686\exp(-5.63\ BD)} \qquad [106]$$

$$\S = \frac{SW}{(0.356 - 0.144\ BD)\ Z_M} \qquad [107]$$

and

$$DD = DP\exp\left[\ln\left(\frac{500}{DP}\right)\left(\frac{1-\S}{1+\S}\right)^2\right] \qquad [108]$$

where DP is the maximum damping depth for the soil layer in mm, BD is the soil bulk density in t/m^3, Z_M is the depth of the lowest soil layer from the surface, and § is a scaling parameter.

5-1.6 Crop Growth Model

5-1.6.1 Potential Growth

A single model is used in EPIC for simulating all the crops considered (corn, grain sorghum, wheat, barley, oats, sunflowers, soybeans, alfalfa, cotton, peanuts, and grasses). Of course, each crop has unique values for the model parameters. Crop growth for both annual and perennial plants can be simulated. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops (alfalfa and grasses) maintain their root systems throughout the year, although the plant becomes dormant after frost. They start growing when the average daily air temperature exceeds the base temperature of the plant.

Energy interception is estimated with the equation

$$PAR = 0.02092(RA)\left(\frac{HRLT}{12}\right)^3\left(1.0 + \frac{\Delta HRLT}{\Delta t}\right)^2 \{1.0 - \exp[-0.65(LAI + 0.05)]\} \qquad [109]$$

where PAR is the photosynthetic active radiation in MJ/m^2, HRLT is the daylight time during a 24-h period in h, and $\Delta HRLT/\Delta t$ is the change in daylight time during a 24-h period.

The potential increase in biomass for a day can be estimated with the equation

$$\Delta B_p = (BE)(PAR) \qquad [110]$$

where ΔB_p is the daily potential increase in biomass in kg/ha and BE is the crop parameter for converting energy to biomass in kg/MJ. The leaf area index (LAI), a function of biomass, is estimated with the relationships

$$LAI = \frac{(LAI_{mx})(WLV)}{WLV + 5512\exp(-0.000608\,WLV)}, \qquad B_l \leq DLAI \qquad [111]$$

$$LAI = LAI_o\left(\frac{1 - B_l}{1 - DLAI}\right)^2, \qquad B_l > DLAI \qquad [112]$$

where LAI_{mx} is the maximum LAI potential for the crop, WLV is the above-ground biomass minus yield in kg/ha, DLAI is the fraction of the growing season when LAI starts declining, and LAI_o is the LAI value from Eq. [111] when B_l = DLAI.

Accumulated biomass after the yield-initiation stage of crop growth is designated as crop yield, using the equations

$$\Delta YLD = 0.0, \qquad \frac{\Sigma RA}{PRA} \leq 0.8\,(1.0 - 1.0/GK) \qquad [113]$$

$$\Delta YLD = \Delta B_p, \qquad \frac{\Sigma RA}{PRA} > 0.8\,(1.0 - 1.0/GK) \qquad [114]$$

$$YLD \leq B_p/GK \qquad [115]$$

where

GK is the ratio of total biomass to crop yield under favorable growing conditions,

ΔYLD is the amount of increase in yield during one day in kg/ha,

YLD is the accumulated yield in kg/ha, and

PRA is the potential solar radiation for the growing season in J/m^2.

Since yield is not allowed to occur until the later part of the growing season, late season stresses may reduce yield more than early season stresses. The amount of root growth for a day is estimated with the equation

$$\Delta RWT = \Delta B_P\,(0.4 - 0.2\,B_l) \qquad [116]$$

where ΔRWT is the daily change in root weight in kg/ha. Daily root sloughing is estimated with the equation

$$\Delta RWS = 0.1\,(\Delta B_P)\,(B_l) \qquad [117]$$

where ΔRWS is the amount of root sloughing during a day in kg/ha. The change in root weight through the root zone is simulated as a function of plant water use and accumulated root weight in each soil layer using the equation

$$RW_j = RW_{oj} + (\Delta RWL)\,(RWF)_j \qquad [118]$$

where RW_0 and RW are the root weights in soil layer j at the start and end of a day in kg/ha, ΔRWL is the change in live root weight during a day in kg/ha, and RWF is a root-weight distribution factor. The daily change in live roots is computed by subtracting the sloughed roots from the total root growth:

$$\Delta RWL = \Delta RWT - \Delta RWS \qquad [119]$$

The root-weight distribution factor is determined by considering the sign of ΔRWL:

$$RWF = \frac{u_i}{\sum_{i=1}^{M} u_i}, \qquad \Delta RWL > 0 \qquad [120]$$

$$RWF = \frac{RW_i}{\sum_{i=1}^{M} RW_i}, \qquad \Delta RWL < 0 \qquad [121]$$

Equations [120] and [121] simply distribute root growth as a function of water use if the root weight is increasing and as a function of existing root weight if the root weight is decreasing. Rooting depth is simulated as a function of heat units and potential root-zone depth:

$$\Delta RD = 2(RZ)(HU)/PHU, \qquad RD \leq RZ \qquad [122]$$

where ΔRD is the daily change in crop root depth in mm.

5-1.6.2 Growth Constraints

If one of the plant stress factors is less than 1.0, the potential biomass predicted with Eq. [110] is adjusted daily, using the equation

$$\Delta B = (\Delta B_P)(REG) \qquad [123]$$

where REG is the crop-growth regulating factor (the minimum stress factor). The water stress factor is computed by considering supply and demand in the equation

$$WS = \frac{E_P}{\sum_{i=1}^{M} u_i} \qquad [124]$$

where WS is the water stress factor with values from 0 to 1. The value of E_P is predicted in the evapotranspiration model, and u_i is a function of depth and soil-water content:

$$u_{pi} = \left(\frac{E_P}{1 - \exp(-\Lambda)}\left(1 - \exp(-\Lambda)\frac{RD_i}{RZ}\right) - \sum_{j=1}^{i-1} u_j\right)(RGF) \qquad [125]$$

where u_{pi} is the potential water use for layer i in mm/d, RGF is the root-growth stress factor with values from 0 to 1, and Λ is a parameter describing water-use rate as a function of root depth. The details of evaluating Λ are given by Williams and Hann (1978). The value of Λ used in EPIC (3.065) assumes that about 30% of the total water used comes from the top 10% of the root zone. Equation [125] allows roots to compensate for water deficits in certain layers by using more water in layers with adequate supplies. The potential water use must be adjusted for water deficits to obtain the actual use for each layer:

$$u_i = u_{pi}, \qquad SW > 0.25\ UL \qquad [126]$$

$$u_i = u_{pi}\,(SW/0.25\ UL), \qquad SW \leq 0.25\ UL \qquad [127]$$

The temperature stress factor is computed with the equation

$$TS = \exp[\Omega(T_o - T/T)^2] \qquad [128]$$

where TS is the temperature stress factor with values from 0 to 1, Ω is the temperature stress parameter for the crop, T_o is the optimal temperature for the crop in °C, and T is the daily average air temperature in °C. The stress parameter is evaluated by appropriate substituting and rearranging of Eq. [128]:

$$\Omega = \frac{\ln(0.9)}{\left(\dfrac{T_o - [(T_o + T_b)/2]}{(T_o + T_b)/2}\right)^2} \qquad [129]$$

where T_b is the base temperature for the crop in °C. Equation [129] sets TS = 0.9 when the air temperature is halfway between T_b and T_o.

The nitrogen and phosphorus stress factors are based on the ratio of accumulated plant N and P to the optimal values. The stress factors vary nonlinearly from 1.0 at optimal levels of N and P to 0.0 when N or P is half the optimal level. The N stress factor is computed with the equation

$$SN_{IDA} = 1 - \frac{SN_{S,IDA}}{SN_{S,IDA} + 29.534\exp(-10.93\ SN_{S,IDA})} \qquad [130]$$

where SN_{IDA} is the N stress factor for day IDA and $SN_{S,IDA}$ is a scaling factor that allows SN to range from 0.0, when the ratio $UN/c_{NB} \bullet B$ is equal to 0.5, to 1.0 when the ratio is 1.0. The P stress factor is computed with Eq. [130] written in P terms. Finally, the value of REG is determined as the minimum of WS, TS, NS, and PS. REG is used to adjust YLD, RWT, and RWL with equations similar to Eq. [123].

The root-growth stress factor is the minimum of stresses caused by soil strength, temperature, and aeration. Temperature stress for each soil layer is computed using Eq. [128]. Stress caused by poor aeration is estimated with the equations

$$AS = \exp[23\,(0.85 - SWF)], \qquad SWF > 0.85 \tag{131}$$

$$AS = 1.0, \qquad SWF \leq 0.85 \tag{132}$$

where AS is the aeration stress factor and SWF is the soil-water factor computed from Eq. [68]. Stress from soil strength is estimated as a function of soil texture and bulk density using the equation

$$SS = 0.1 + \frac{0.9\,BDP}{BDP + \exp[bt_1 + (bt_2)\,(BDP)]} \tag{133}$$

where SS is the soil strength factor, BDP is the soil bulk density, and bt_1 and bt_2 are parameters dependent on soil texture. The values of bt_1 and bt_2 are obtained by considering boundary conditions for stress. The lower boundary where stress is essentially nil is given by the equation (Jones, 1983):

$$BD1 = 1.15 + 0.00445\,SAN \tag{134}$$

where BD1 is the bulk density that gives no stress (SS = 1.0) for a particular percentage of sand, SAN. The upper boundary is given by the equation (Jones, 1983):

$$BD2 = 1.5 + 0.005\,SAN \tag{135}$$

where BD2 is the bulk density that gives SS ~ 0.2 for a particular percentage of sand, SAN. The equations for estimating bt_1 and bt_2 are

$$bt_2 = \frac{\ln(0.0112\,BD1) - \ln(8\,BD2)}{BD1 - BD2} \tag{136}$$

$$bt_1 = \ln(0.0112\,BD1) - (bt_2)\,(BD1) \tag{137}$$

Equations [136] and [137] assure that Eq. [133] gives SS values of 1.0 and 0.2 for BDP equal BD1 and BD2. Finally, the root-growth stress factor, RGF, is the minimum of AS, SS, and TS. Besides constraining water use as defined in Eq. [125], RGF also constrains rooting depth. Combining RGF with Eq. [122] gives

$$\Delta RD = 2\,(RZ)\,(HU)\,(RGF)/PHU, \qquad RD \leq RZ \tag{138}$$

5-1.7 Tillage

The EPIC tillage component was designed to mix nutrients and crop residue within the plow depth, simulate the change in bulk density, and convert standing residue to flat residue. Each tillage operation is assigned a mixing efficiency with values from 0 to 1. The tillage mixing equation is

$$X_i = (1 - EF)\, X_{oi} + \left(\frac{Z_i - Z_{i-1}}{PD}\right) EF \sum_{j=1}^{M} X_{oj} \qquad [139]$$

where X_i is the amount of the material in layer i after mixing in kg/ha, EF is the mixing efficiency of the tillage operation (0-1), X_{oj} is the amount of the material in layer j before mixing in kg/ha, and M is the number of soil layers in the plow depth (PD) in mm.

The change in bulk density in the plow layer is simulated for each tillage operation using the equation

$$BDP_i = BDP_{oi} - (BDP_{oi} - 2/3\, BD_{oi})\,(EF) \qquad [140]$$

where BDP_o is the bulk density in soil layer i before tillage in t/m^3, BD_o is the bulk density of the soil when it has completely settled after tillage, and BDP is the bulk density after tillage. Between tillage operations, the soil settles with each rainfall according to the equations

$$SZ_i = \frac{O_{i-1}}{Z_i^{0.6}}\left[1.0 + \frac{2.0\, SAN_i}{SAN_i + \exp(8.597 - 0.075\, SAN_i)}\right] \qquad [141]$$

and

$$BDP_i = BDP_i + (BD_i - BDP_i)\left[\frac{SZ_i}{SZ_i + \exp(3.735 - 0.008835\, Z_i)}\right] \qquad [142]$$

where SZ_i is a scaling factor for soil layer i, O_{i-1} is the amount of water that percolates into the layer in mm (R-Q for the top layer), and SAN is the percentage of sand in the layer.

Another important function of the tillage model, converting standing residue to flat residue, is done with the equation

$$SR = (SR_o) \exp[-0.0569\, (PD)\, (EF)^2] \qquad [143]$$

where SR_o and SR are the standing residue weights before and after tillage in kg/ha and PD is the plow depth in mm.

Other functions of the tillage component include simulating row height and surface roughness. Both these variables are specified for each tillage implement. The user also specifies the date and depth for each tillage operation. The tillage operation is carried out on the specified date if the soil is dry enough; if not, on the next suitable day.

The EPIC model can simulate three kinds of harvest: (i) traditional harvest that removes seed, fiber, etc. (multiple harvests are allowed for crops like cotton); (ii) hay harvest (multiple harvests are allowed); and (iii) no harvest (green manure crops, etc.). The traditional harvest partitions the crop stover into 10% residue on the top soil layer and 90% standing residue. A shredder is often applied after harvest, which further partitions the residue according to the height before and after cutting. Yield from a hay harvest is also estimated for height before and after cutting.

5-1.8 Economics

The crop budgets are calculated with components from the crop budget generator developed at Oklahoma State University (Kletke, 1979). Budgets can be calculated for each year in the EPIC simulation or for the average yields and resource requirements for the period of simulation.

Inputs are divided into two categories: fixed and variable. Fixed inputs include depreciation; interest or return on investment; insurance; and taxes on equipment, land, and capital improvements (terraces, drainage, irrigation systems, etc.). Variable inputs are defined as machinery repairs, fuel and other energy, machine lubricants, seed, fertilizer, pesticides, labor, and irrigation water.

Total variable cost is expressed with the equation

$$TVC = \sum_{i=1}^{M} (PR_i)(QA_i) \qquad [144]$$

where TVC is the total variable cost in dollars, PR is the price of the variable input (i) in dollars, and QA is the quantity of the input used per ha.

The machinery complement file is a list of 100 pieces of equipment for use in simulating user-specified tillage operations. This file contains equipment information like purchase price, size, expected life, and repair cost. With this information, fixed costs for the machinery are allocated to each crop on an hours-of-use basis. Equations [145] through [149] are used for the fixed costs of machinery.

$$DEPC = (PP - SV)/(HUA)(YRO) \qquad [145]$$

where DEPC is the depreciation cost in dollars/hr, PP is the purchase price in dollars, SV is the salvage value in dollars, HUA is the annual use in h, and YRO is the time the equipment is owned in yr.

$$AI = (PP + SV)/2\,HUA \qquad [146]$$

where AI is the average investment in dollars/h.

$$IC = (AI)\,(IT) \qquad [147]$$

where IC is the interest cost in dollars/h and IT is the interest rate.

$$INSC = (AI)\,(INSR) \qquad [148]$$

where INSC is the insurance cost in dollars/h and INSR is the insurance rate.

$$MTAX = (PP)(TR)/HUA \qquad [149]$$

where MTAX is the machinery tax in dollars and TR is the tax rate.

Machine variable cost is also calculated on a per-hour basis.

$$PL = (HUA)(YRO)/HOL \qquad [150]$$

where PL is the percentage of machinery life used in a given year and HOL is the total machine life in h.

Total accumulated repair cost is calculated with the equation

$$TAR = (rc_1)\,(PP)\,(rc_2)\,(PL)\,(rc_3) \qquad [151]$$

where TAR is the total accumulated cost of repairs in dollars and rc_1, rc_2, and rc_3 are repair cost coefficients (American Society of Agricultural Engineers, 1971). Repair cost is placed on an hourly basis using the equation

$$rc = TAR/(HUA)(YRO) \qquad [152]$$

Fuel-consumption cost is given by the equation

$$CF = (DH)\,(CFM)\,(PF) \qquad [153]$$

where CF is the fuel-consumption cost in dollars/h, DH is the drawbar horsepower, CFM is the fuel-consumption coefficient, and PF is the price of the fuel in dollars/liter. Lubrication cost is estimated as 15% of the fuel cost.

Actual annual cost of operating machinery can be estimated by converting from cost/h to cost/ha using the equation

$$HPA = 10/(VT)(WD)(FE) \quad [154]$$

where HPA is the time required to till 1 ha in h, VT is the tractor velocity in km/h, WD is the implement width in m, and FE is the field efficiency of the equipment. Finally, total annual machinery cost is estimated by summing the costs of the individual operations.

Fixed costs like rent, land taxes, and management are also charged on a per-ha basis. Total cost is the sum of the variable and fixed costs.

Gross income from the crop is simply the market price of the crop times the yield minus any marketing or harvest cost not accounted for in the machinery cost. Net profit, of course, is the difference between gross income and total cost. Simulated annual net profits are useful in illustrating the effects of erosion.

5-2 MODEL TESTS

Simulations of EPIC have been performed on 150 test sites in the continental USA and 13 sites in Hawaii. Table 5-1 shows runoff and sediment yield results from three small watersheds in Falls County, TX. More tests are planned for these components of the model, although they have been tested extensively (Knisel, 1980; Williams, 1982). Crop yield results are shown in Tables 5-2 to 5-4. Table 5-2 shows comparisons of simulated and recently measured yields for 12 research plots. Older, long-term average yields from 8 research plots are compared with simulated yields in Table 5-3. The estimated yields in Table 5-4 (county averages, local experts' estimates, etc.) are compared with simulated yields. Table 5-5 shows results of simulated wind erosion. Although there are no measurements of wind

Table 5-1. Comparisons of simulated and measured runoff and sediment yield in Falls County, TX.

		Annual runoff				Annual sediment yield			
		Mean		SD		Mean		SD	
Watershed	Yr	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
		mm				t/ha			
W-10	5	246	264	126	131	0.082	0.082	0.098	0.044
SW-11	4	150	140	139	125	1.33	1.11	0.93	0.82
Y-14	4	204	245	138	164	0.82	1.04	1.11	1.81

erosion with which to compare the simulations, the results are similar to estimates obtained using the annual wind-erosion equation.

To determine the model's sensitivity to erosion, crop yields were related to accumulated erosion for the 50-yr simulation periods. The resulting linear regression equations were used to compare expected yields at the start and end of the 50-yr period. Generally, the regression analysis indicated a reduction in crop yield depending on soil and climatic characteristics and fertilization rate. In some areas with high erosion rates and unfavorable subsoil, crop yield was reduced as much as 40%.

Table 5-2. Comparisons of simulated and recently measured crop yields.

				Yield		Standard deviation	
State	County	Yr	Crop	Measured	Simulated	Measured	Simulated
				kg/ha			
IA	Monona	5	Corn	6996	7653	1110	1035
IA	Monona	5	Oats	1755	2225	774	1000
IA	Monona	10	Corn	6162	7325	1908	1895
IA	Ringold	7	Corn	7270	7235	1702	798
IA	Ringold	7	Soybean	1910	2065	284	531
IA	Ringold	10	Corn	6593	7095	1296	1075
IA	Story	5	Corn	6664	7580	815	790
IA	Story	5	Corn	6575	7265	922	1215
IA	Story	5	Corn	6077	7250	1279	1210
IA	Story	4	Corn	7033	7205	1010	1175
MO	Boone	10	Corn	7833	7632	2077	1635
OH	Coshocton	3	Corn	8399	7460	2665	2020

Table 5-3. Comparisons of simulated and long-term average measured crop yields.

				Yield	
State	County	Yr	Crop	Measured	Simulated
				kg/ha	
AL	Escambia		Soybeans	1893	1911
			Corn	5290	5350
			Wheat	1231	1584
AL	Escambia		Corn	5278	5325
			Cotton	2470	1415
ND	Morton	29	Corn	1625	2060
			Wheat	1022	835
ND	Stark	40	Corn	879	1015
			Wheat	908	625
MT	Hill	31	Corn	659	1040
			Wheat	800	565
WY	Sheridan	30	Corn	910	1185
			Wheat	1204	835
WY	Laramie	32	Corn	816	1165
			Wheat	693	825
KS	Ellis	31	Grain sorghum	1280	3450
			Wheat	1480	1550

Table 5-4. Comparisons of simulated and estimated crop yields.

State	County	Crop	Yield Estimated	Yield Simulated
			kg/ha	
AL	Conecuh	Peanut	3 500	2 885
AZ	Cochise	Pasture	1 000	1 290
AZ	Maricopa	Cotton	2 500	2 505
AZ	Yuma	Cotton	3 760	3 065
		Alfalfa	15 700	21 685
CO	Washington	Corn	2 511	3 135
		Wheat	982	1 570
GA	Emanual	Corn	6 275	6 155
		Wheat	3 700	1 665
		Cotton	2 520	2 410
GA	Oconee	Soybean	2 020	2 395
		Grain sorghum	4 710	5 605
IL	Marion	Corn	4 269	6 875
		Soybean	1 567	2 410
KS	Ellis	Wheat	1 930	2 250
KS	Finney	Corn	8 440	8 280
KS	Greeley	Corn	9 500	9 785
KS	Sherridan	Corn	10 044	11 265
KS	Thomas	Corn	2 084	2 240
		Wheat	1 765	1 066
KY	Caldwell	Soybean	1 850	2 390
		Corn	4 960	6 455
		Wheat	2 333	2 270
KY	Fayette	Corn	5 660	
MN	Polk	Wheat	2 450	3 000
		Alfalfa	5 160	5 420
MS	Hinds	Soybean	2 200	2 305
MS	Oktibbeha	Corn	2 373	4 225
		Soybean	1 338	1 420
MS	Sunflower	Cotton	1 929	2 085
MT	Gallatin	Wheat	2 470	2 465
MT	Judith Basin	Wheat	1 470	1 110
		Corn	2 260	2 350
MT	Richland	Wheat	1 790	2 295
NC	Craven	Corn	4 457	6 280
		Peanut	2 330	2 290
ND	Morton	Wheat	1 880	2 315
NE	Cheyenne	Wheat	2 340	2 065
NE	Red Willow	Wheat	2 640	2 500
NM	Curry	Wheat	1 000	1 390
		Alfalfa	10 760	7 525
NM	Eddy	Corn	6 025	9 125
		Wheat	2 970	3 410
		Cotton	2 240	2 775
OH	Coshocton	Corn	5 900	6 540
		Wheat	2 170	3 245
OK	Canadian	Wheat	1 855	2 070
OK	Comanche	Grain sorghum	1 505	1 855
		Wheat	1 010	1 215
SD	Bennett	Wheat	2 020	2 440
SD	Lyman	Wheat	1 960	2 350
TN	Marshall	Soybean	1 540	1 245
		Corn	3 365	4 415

(continued on next page)

Table 5-4. Continued.

State	County	Crop	Yield: Estimated	Yield: Simulated
			kg/ha	
TX	Bell	Grain sorghum	4 620	4 215
		Cotton	1 655	1 960
		Wheat	2 220	2 485
TX	Hartley	Corn	940	1 151
TX	Howard	Cotton	1 315	1 095
TX	Potter	Grain sorghum	6 100	6 350
		Wheat	2 800	3 025
WA	Whitman	Wheat	4 500	3 930

Table 5-5. Simulated wind erosion.

State	County	Crop	Soil erodibility factor	Climate factor	Soil loss
					t/ha
AZ	Yuma	Corn	300	495	46
		Alfalfa			
CO	Prowers	Wheat	150	75	0
CO	Washington	Corn	193	75	31
		Wheat			
IA	Harrison	Corn	193	16	3
IA	Monona	Corn	193	18	1
		Soybean			
KS	Finney	Corn	193	100	47
KS	Greeley	Corn	193	97	43
KS	Sherman	Corn (irrigated)	108	94	6
ND	McLean	Wheat	108	58	0
ND	Morton	Corn	193	37	26
		Wheat			
NE	Cheyenne	Wheat	125	54	1
NE	Red Willow	Wheat	108	32	0
		Grain sorghum			
NM	Curry	Wheat	300	93	34
		Grain sorghum			
NM	Quay	Cotton	125	116	73
		Grain sorghum			
NV	Churchill	Oats	300	36	0
		Alfalfa			
OH	Auglaize	Corn	108	4	0
		Soybean			
OK	Comanche	Grain sorghum	193	20	16
SD	Bennett	Wheat	108	48	0
SD	Lyman	WHeat	193	50	1
TX	Bailey	Cotton	300	105	125
TX	Carson	Wheat	193	105	1
TX	Deaf Smith	Wheat	193	105	14
		Grain sorghum			
TX	Gaines	Cotton	695	202	717
TX	Howard	Cotton	193	120	65

5-3 CONCLUSIONS

The EPIC model is operational and has produced reasonable results under a variety of climatic conditions, soil characteristics, and management practices. It has also demonstrated sensitivity to erosion in terms of reduced crop production.

More extensive testing is planned for EPIC. Although some components of the model such as hydrology and erosion are based on accepted technology, other components require rigorous testing for validation. The two components that most need testing are crop growth and nutrients, because they are newly developed and are extremely important to the success of the EPIC model.

The model has many potential uses beyond the RCA analysis, including: (i) national conservation policy studies, (ii) national program planning and evaluation, (iii) project-level planning and design, and (iv) as a research tool.

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