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Agricultural Policies and Soil Degradation in Western Canada: An Agro-Ecological Economic Assessment (Report 2: The Environmental Modelling System)

(Technical Report 5/93)

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A diskette containing this working paper in Wordperfect 5.2 files is available from the Economic Analysis Division upon request.

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I. INTRODUCTION

The Prairie Farm Rehabilitation Administration (PFRA) estimated that farmers in Alberta, Saskatchewan, and Manitoba lost $100 million in 1990 as a result of soil degradation, representing as much as a 10 percent drop in farm income from cash crops (PFRA 1990). In spite of this, farmers in Western Canada have been able to maintain productivity by taking advantage of improved agricultural technology, which often masks over the serious environmental problems that are occurring from soil degradation. Considerable attention is currently focused in Canada on the potential exacerbation of these environmental problems by the Gross Revenue Insurance Program (GRIP) and the Net Income Stabilization Account (NISA) that were introduced under the Farm Income Protection Act (FIPA) in 1991. There is growing concern that GRIP and NISA are not resource neutral and will influence producers to bring environmentally sensitive land, highly susceptible to erosion and marginally productive, into production. To evaluate the resource neutrality of GRIP and NISA with emphasis on land use and soil degradation, an integrated agro-ecological economic system, built around Agriculture Canada's Regional Agricultural Model (CRAM) (Horner et al. 1992), is being developed for Western Canada (Alberta, Saskatchewan, and Manitoba). The conceptual framework for the entire integrated system is described in detail by Agriculture Canada (1993).

The major soil degradation problems observed on the prairies are wind and water erosion, salination, and organic matter depletion (PFRA 1990). Additional soil degradation and environmental concerns have been raised over soil compaction, and surface and groundwater quality degradation from agricultural nonpoint sources of pesticides and nutrients. The environmental modelling system discussed here will be configured to directly address the problems of wind and water erosion, organic matter depletion, and nutrient (nitrogen) movement under the scenarios of GRIP and NISA. The system will be designed to be as flexible as possible to accommodate other program scenarios and additional environmental indicators for future policy analyses.

The environmental modelling system (subblock) required for the analysis is shown in Figure 1 within the general conceptual framework for the entire integrated system. The key component of the environmental subblock is the Erosion Productivity Impact Calculator (EPIC), which was developed by the USDA-ARS to estimate the long-term impacts of erosion upon soil productivity (Williams et al. 1984, Williams 1990). The interface between the environmental subblock and economic subblock (i.e., resource-sensitive CRAM or RS-CRAM) is accomplished by constructing environmental and yield distribution metamodels (response functions) based on an experimentally designed set of EPIC simulations (Figure 2). Erosion costs are not calculated internally in RS-CRAM; the intent rather is to provide erosion rate estimates with EPIC.

The metamodels are used to output key environmental indicators and annual crop yields as a function of policy, management practice, crop rotation, input use, and location. Every time a policy scenario is evaluated, the economic model simulates the behavioral responses to the policy and passes its production results to the ecological block for generating environmental indicators; a trade-off analysis is then performed. This integrated systems approach requires a careful definition of the policies to be analyzed before the actual system is built.

The report is ordered by the following four major sections: the EPIC model; the environmental database; calibration and testing of EPIC; and, a summary.

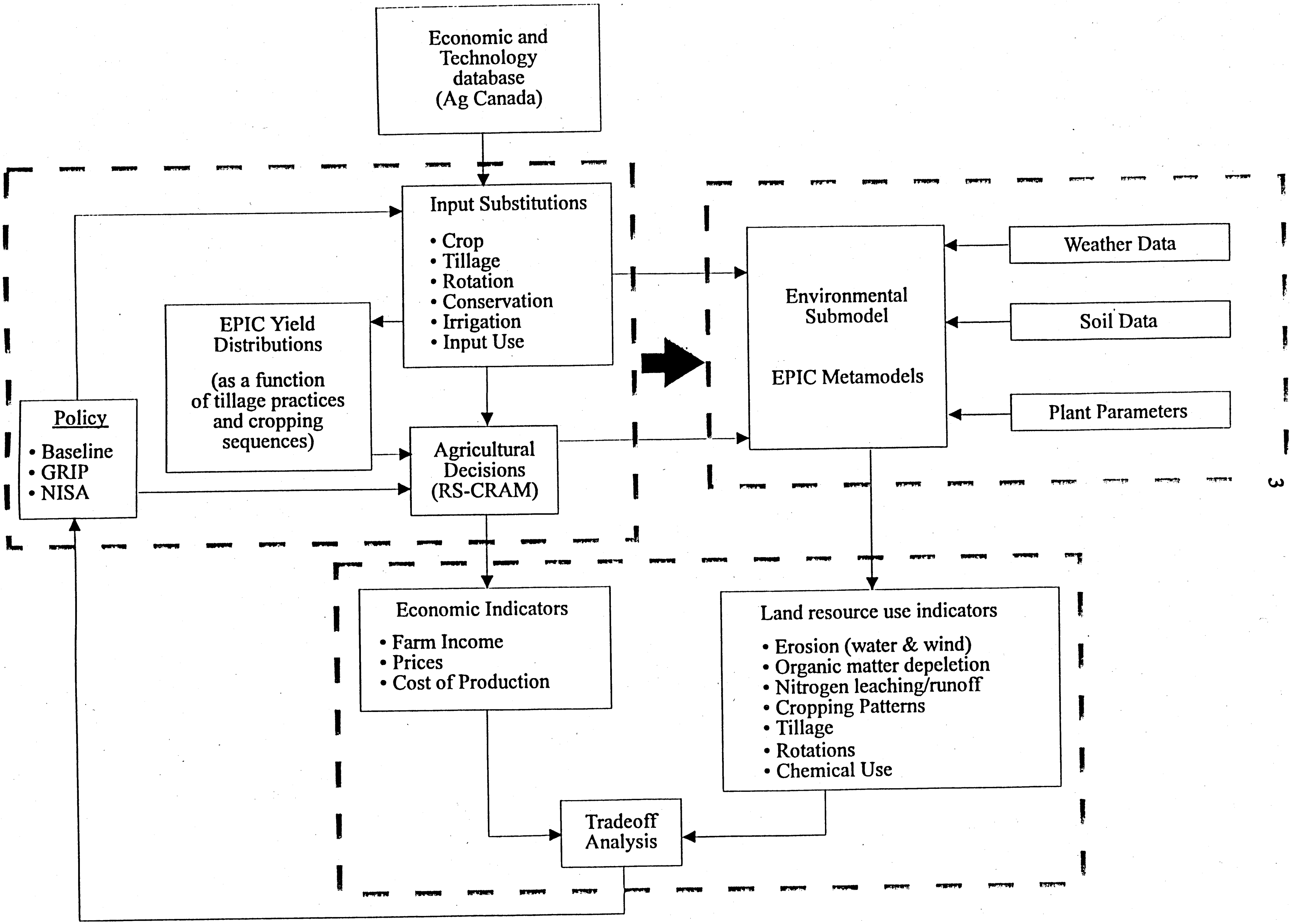

Figure 1. General conceptual framework

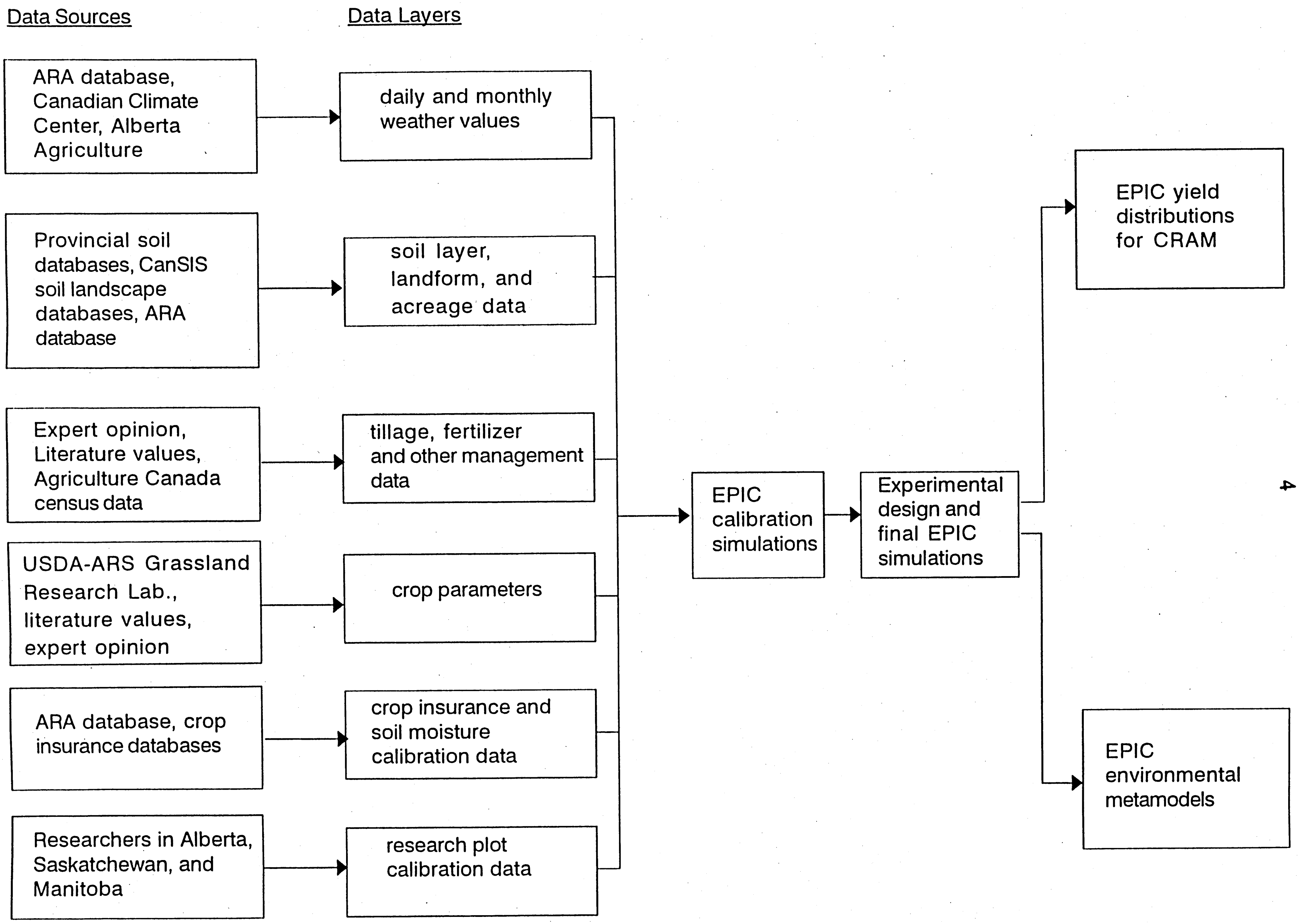

Figure 2. Schematic of EPIC data inputs and simulation runs

II. THE EPIC MODEL

A. Historical Background

The 1977 Soil and Water Resource Conservation Act (RCA) set forth the requirements that the U.S. Secretary of Agriculture develop long-term policy decisions regarding the use and protection of soil and water resources. The initial implementation of the RCA revealed that there were no reliable tools to assess soil erosion costs and the benefits that would result from controlling soil erosion (Williams 1990). In response, a national U.S. Agricultural Research Service (ARS) erosion-productivity modelling team was assembled during 1981 to develop a model that could: (1) realistically simulate important processes within a physically based framework with readily available inputs; (2) simulate the long-term impacts of erosion for hundreds of years; (3) be applied to a wide range of U.S. soils, crops, and weather conditions; and (4) assess the impact of different management scenarios on erosion and soil productivity in an efficient manner. The product of this effort was the EPIC model.

The first major application of EPIC was for the 1985 RCA analysis (Putman et al. 1985). Approximately 12,000 100-year EPIC simulations were performed in support of the analysis to develop erosion-productivity relationships across the United States. These relationships were coupled with production costs, normalized yields, and prices by the Center for Agricultural and Rural Development (CARD), Iowa State University in order to complete the analysis. Since the 1985 RCA analysis, the number of EPIC Users has expanded greatly in several countries. The types of problems to which the model is being applied have also increased, as shown by the examples listed in Table 1. The model is now distributed as the "EPIC Water Quality Model," reflecting the increased interest on nonpoint source pollution of water sources. However, it will simply be referred to as EPIC for the remaining discussion.

B. Model Structure

The EPIC model consists of ten major subcomponents as listed in Table 2. These subcomponents are interfaced through a main program that controls inputs, outputs, and data flow between subroutines. Flexibility is provided to the user in setting up input files and choosing output steps (daily, monthly, or annual). For this project, EPIC version 3090 will be used; it incorporates an improved wind erosion model (Williams et al. 1992). This is an important enhancement because of the major wind erosion problems that exist in some regions of the Prairie Provinces.

The Universal Text Integration Language (UTIL) program is provided with EPIC to preprocess input files. Also, a standard set of data and EPIC control files are provided to help construct the input files and manipulate the output (Table 3). The crop, tillage, pesticide, fertilizer, and miscellaneous parameter files can all be accessed through UTIL in support of constructing input files. Weather generator tables and soil layer data files are also provided for the United States.

A general description of the major subcomponents is provided here based on documentation provided by Williams et al. (1984), Williams (1990), and Sharpley and Williams (1990). These documents should be consulted for more detailed descriptions of the different functions used in each subcomponent.

Table 1. Example EPIC applications

Source	Application
Krishna et al. (1987)	Impact of furrow-dikes on runoff and sorghum yields for three sites in Texas
Steiner et al. (1987)	Comparison between observed and predicted ET, runoff, soil water, and crop yield for a dryland wheat-sorghum-fallow crop rotation over the period 1958-84 at Bushland, TX
Benson et al. (1989)	Long-term impacts of soil erosion on four soils in four different U.S. regions
Jones et al. (1989)	AUSCANE; modified version of EPIC developed to simulate sugarcane growth in Australia
Cabelguenne et al. (1990)	Comparison between observed and predicted yields for corn, grain sorghum, sunflower, soybean and wheat grown in 5-year rotations, at three levels each of fertilizer, irrigation, and tillage, in Southern France
Robertson et al. (1990)	The effect of temperature, precipitation, and $C0_2$ changes in crop yield estimated for several U.S. locations by the ARS and SCS
Williams et al. (1990a)	Simulation of the impact of furrow diking at 23 locations in Louisiana, New Mexico, Oklahoma, and Texas
Arbeitsgruppe Systemforschung (1991)	Assessment of nitrate leaching from manure applications for approximately 3,000 farms in Landkreis (County) Vechta in Lower Saxony, Germany
Engelke and Fabrewitz (1991)	Evaluation of the nitrogen subcomponent with data from European research sites
Sabbagh et al. (1991a)	EPIC-WT; modified version of EPIC that incorporated functions from DRAINMOD to better simulate shallow water table soil conditions containing subsurface drainage
Sabbagh et al. (1991b)	EPIC-PST; modified version with GLEAMS pesticide movement routines incorporated
Kiniry et al. (1992a)	Simulation of sunflower yields were performed with EPIC and ALMANAC over a wide range of environments and management options
Kiniry et al. (1992b)	ALMANAC; modified version of EPIC designed to simulate the growth and development of two competing plant species

Table 2. Subcomponents of the EPIC model

Subcomponent	
Weather	Daily inputs of precipitation, maximum and minimum temperature, solar radiation, wind, and relative humidity; historical and/or generated inputs can be used
Hydrology	Processes of surface runoff, percolation, lateral subsurface flow, evapotranspiration, and snow melt
Erosion	Both wind and water erosion are simulated; three options are available to simulate water erosion
Nutrients	Processes of nitrogen and phosphrous transformations, crop uptake, leaching, and runoff (both solution and eroded phases)
Soil temperature	Calculated as a function of air temperature and ground cover
Crop growth	A generic crop growth model is used that permits the simulation of complex rotations
Tillage	Different levels of tillage can be simulated; specific implements are accounted for
Plant environment control	Different levels of irrigation, fertilizer, and lime; drainage and furrow diking can be simulated
Pesticide fate	Pesticide routines from the GLEAMS model have been incorporated; processes of pesticide degradation, leaching, and runoff (both solution and eroded phases)
Economics	Crop budgets

Table 3. Description of standard data and control files provided with EPIC [a,b]

File	Description
Crop parameter	Data related to crop characteristics.
Tillage parameter	Information about tillage, planting, harvesting, and other equipment.
Pesticide parameter	Data on pesticides used to control weeds and insects.
Fertilizer parameter	Information on inorganic and organic fertilizers.
Miscellaneous parameter	Miscellaneous data that can be used to modify model sensitivity to a variety of processes. It should be modified only in consultation with model developers or by very experienced users.
Graphics control	Controls the parameters to be automatically graphed as the EPIC model is executed.
Multi-run	Controls execution of multiple runs in which the water and wind erosion factors can be varied to estimate the long-term impacts of soil erosion.
Print	Specifies which output parameters will be printed in the monthly, daily, and summary outputs.
Daily weather	Daily weather data that is read by the model (in place of generating input weather data stochastically).

[a] From Dumesnil (1992).

[b] Weather generator and soil layer data files are also provided for the U.S.

The reader is referred to the original EPIC Users Manual (Williams et al. 1990b) and to an updated EPIC Users Manual edited by Dumesnil (1992) to obtain a complete listing of model inputs and guidelines in running EPIC.

B.1. Weather

EPIC functions on a daily timestep and is driven by either historical and/or generated daily weather inputs including precipitation (mm), maximum and minimum temperature (C), solar radiation (MJ/m^2), relative humidity (%), and windspeed (m/s). Relative humidity is required only if the Penman-Monteith option of estimating potential evaporation is used (see section II.B.2.). Wind speed is also required for the Penman-Monteith option as well as for calculating wind erosion.

If historical data from climate stations are unavailable, a weather generator can be used to generate the required EPIC daily inputs using monthly weather generator statistics (Table 4). Several options are also provided for inputting climate data in combination with generated weather. For example, historical daily values can be input for precipitation and maximum and minimum temperatures, while solar radiation, relative humidity, and wind speed values are generated. Also, provision is made for generating missing values within climate station data by inserting the appropriate codes in the data record wherever there is a missing value.

Table 4. EPIC weather generator parameters[a]

EPIC Variable	Definition	Units
OBMX	Average monthly maximum air temperature	C
OBMN	Average monthly minimum air temperature	C
SDTMX	Monthly standard deviation maximum daily air temperature	C
SDTMN	Monthly standard deviation minimum daily air temperature	C
SMY	Average monthly precipitation	mm
RST(2)	Monthly standard deviation of daily precipitation	mm
RST(3)	Monthly skew coefficient for daily precipitation	---
PRW1	Monthly probability of wet day after dry day	---
PRW2	Monthly probability of wet day after wet day	---
WVL	Average number days of rain per month	d
WI	Monthly maximum 0.5-h rainfall for period of record (TP24)	mm
OBSL	Monthly average daily solar radiation	MJ m^{-2}
RH	Monthly average relative humidity	---

[a] From Williams et al. (1990b).

B.2. Hydrology

Runoff volume is calculated in EPIC by using a modified version of the USDA Soil Conservation Service (SCS) runoff curve number method (USDA-SCS 1972). The runoff volume is estimated by the curve number method as a function of daily runoff amount, soil type, land management, and soil-water content with the following equation:

$$Q = \frac{(R - 0.25)^2}{R + 0.8S_R} \tag{1}$$

where Q is the daily runoff (mm), R is the daily rainfall, and S_R is a retention parameter (Q equals 0.0 if R is less than or equal to S_R). The retention parameter S_R varies spatially due to variation in soil type, land use, management, and slope, and temporally because of soil moisture content changes. It is calculated as a function of curve number (CN) (Table 5) for average moisture conditions where

$$S_R = 254 \left(\frac{100}{CN} - 1 \right) . \tag{2}$$

In EPIC, the curve numbers given in Table 5 are assumed to represent a 5 percent slope and are further adjusted for slope variation. Antecedent soil moisture conditions are also taken into account when calculating the partitioning of infiltration and runoff with the curve number approach.

Peak runoff rates are estimated as

$$q_p = \frac{(p)(r)(A)}{360} \tag{3}$$

Table 5. Runoff curve numbers for selected hydrologic soil-cover complexes[a,b]

Cover			Hydrologic soil group			
Land use	Treatment or practice	Hydrologic soil group[c]	A	B	C	D
Fallow	Straight row	---	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	65	82	86
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
	Contoured and terraced	Good	59	70	78	81
Close-seeded legumes[d] or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79

[a] From USDA-SCS (1972).

[b] Antecedent moisture condition II, and $I_a = 0.2S$.

[c] Good condition should be assumed for most soils.

[d] Close-drilled or broadcast.

where q_P is the peak runoff rate (m^3/s), p is a runoff coefficient (equal to Q/R) that describes the watershed infiltration characteristics, r is the rainfall intensity (mm/h) for the watershed's time of concentration, and A is the watershed area (ha). The value of r is determined for specific rainfall events using an exponential distribution. The peak runoff rate q_p is used for estimating water erosion.

A storage routing method is used in EPIC to simulate downward vertical water flow through the layered soil profile. Downward flow in the storage routing technique is governed by the saturated conductivity and occurs when the field capacity of a soil layer is exceeded, providing that the water content of the layer below it has not exceeded field capacity. Drainage from the layer continues until the total amount of water stored in it returns to the field capacity level. Upward flow may be triggered if one of the lower layers exceeds field capacity. If the soil temperature drops to 0° C or below for a soil layer, no percolation is allowed in that layer. Lateral subsurface flow is simulated at the same time as percolation for each soil layer. The model partitions the flow between percolation and lateral subsurface movement on the basis of land slope and saturated conductivity.

Evapotranspiration is calculated in EPIC as a function of potential evaporation of moisture from soil and crops. Four options are provided in EPIC for determining potential evaporation: (1) Hargreaves (Hargreaves and Samani 1985), (2) Penman (Penman 1948), (3) Penman-Monteith (Monteith 1965), and (4) Priestley-Taylor (Priestley and Taylor 1972). The Penman-Monteith and Penman options are considered the most accurate but are also the most data-intensive, requiring solar radiation, air temperature, wind speed, and relative humidity as inputs.

The other two options provide reasonable results if wind speed, relative humidity, and solar radiation data are not available.

Actual soil and plant evaporation are estimated separately using the method developed by Ritchie (1972). Actual plant evaporation is computed as a fraction of the potential plant evaporation based on the amount of plant available water in the soil. Actual soil evaporation is determined as a fraction of the potential soil evaporation based on the soil depth and amount of soil moisture in the upper 0.2 m of the soil.

A linear function of temperature is used to estimate snow melt on days when the maximum temperature exceeds 0° C and snow is present. Runoff volume and percolation are simulated for melted snow in a manner similar to rainfall. However, the peak runoff rate is estimated by assuming that rainfall is uniformly distributed over a 24-hour period, with the rainfall energy factor set to 0.0.

B.3. Water erosion

Water erosion of soil is simulated in EPIC in response to rainfall-runoff events, and for sprinkler and furrow irrigation. Three different options are provided to simulate water erosion: (1) Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978), (2) Modified Universal Soil Loss Equation (MUSLE) (Williams 1975), or (3) the Onstad-Foster (OF) modification of the USLE (Onstad and Foster 1975). Each equation takes the basic form of the USLE:

$$Y_s = X(K)(C)(P)(LS)(R) \tag{4}$$

where Y_s is the sediment yield (t/ha), X is the rainfall energy factor, K is the soil erodibility factor, C is the crop management factor, P is the erosion control practice factor, LS is the slope length and steepness factor, and R is the coarse fragment factor.

The three options differ only in how the rainfall energy factor is calculated:

$$X = EI \qquad \textit{for } \text{USLE} \tag{5}$$

$$X = 11.8(Q^{*} \cdot q_p)^{0.56} \qquad \textit{for MUSLE} \tag{6}$$

$$X = 0.5EI + 3.42Q \cdot q^{*0.33} \qquad \textit{for OF} \tag{7}$$

where EI is the dimensionless rainfall energy factor that is computed as a function of the rainfall energy, Q (mm) and Q^* (m^3) are runoff volumes, and q_p (mm/h) and q^* (m^3/s) are peak runoff rates. Erosive energy is determined in the USLE solely as a function of rainfall. The MUSLE, on the other hand, relies only on runoff variables as indicators of erosive energy while the Onstad-Foster equation uses both the USLE and MUSLE energy factors. The MUSLE is the preferred option because the runoff variables provide advantages over the USLE: improved accuracy, elimination of delivery ratios required to calculate sediment yield, and sediment yields that can be calculated for single storm events rather than being restricted to annual estimates.

Rainfall rates used to calculate rainfall energy are estimated with an exponential distribution. The decay coefficient of the exponential distribution varies from storm to storm. Soil texture and organic matter soil inputs are used to determine the soil erodibility factor K. The crop management factor C is adjusted on days when runoff events occur on the basis of aboveground biomass, crop residue on the surface, and the minimum C factor for the crop. The LS factor is determined as described in section III.A.3. The P factor is determined in the manner described by Wischmeier and Smith (1978). The erosion estimates are adjusted with a nonlinear function of topsoil coarse fragments.

B.4. Wind erosion

Prior to EPIC 3090, a modified form of the Wind Erosion Equation (WEE) (Woodruff and Siddoway 1965) was used to estimate wind erosion in EPIC. Improved simulation of potential wind erosion of a smooth, bare, erodible soil of known length is accomplished in EPIC 3090 with the Wind Erosion Continuous Simulation (WECS) (Williams et al. 1992). Advantages of WECS over previous methodology for EPIC include: (1) a more mechanistic approach, (2) increased sensitivity to management decisions, and (3) wind erosion estimates that are more realistic. Erosion estimates by WECS have been shown in initial testing to vary more between years and within a year as compared with the original wind erosion routine. Required inputs for simulating wind erosion are shown in Table 6.

Potential wind erosion varies nonlinearly with field length in WECS, with maximum erosion rates occurring at long field lengths. The potential erosion is simulated as

$$Y_w = (FI)(FR)(FV)(FD)\int_0^T Y_{rw}\,dt \tag{8}$$

where Y_w is wind erosion (t/ha), FI is the soil erodibility factor, FR is the surface roughness factor, FV is the vegetative cover factor, FD is the mean unsheltered travel distance of wind

Table 6. EPIC wind erosion model inputs[a]

EPIC variable	Definitions	Units
FL	Field length	km
FW	Field width	km
ANG	Clockwise angle of field length from north	degrees
STD	Standing dead crop residue	$t\ ha^{-1}$
SWV	Power of modified exponential distribution of wind speed	--
CF	Climatic factor	--
ACW	Wind erosion adjustment factor	--
WVL	Average monthly wind velocity	$m\ s^{-1}$
DIR(1)	N wind during each month	%
DIR(2)	NNE wind during each month	%
DIR(3)	NE wind during each month	%
DIR(4)	ENE wind during each month	%
DIR(5)	E wind during each month	%
DIR(6)	ESE wind during each month	%
DIR(7)	SE wind during each month	%
DIR(8)	SSE wind during each month	%
DIR(9)	S wind during each month	%
DIR(10)	SSW wind during each month	%
DIR(11)	SW wind during each month	%
DIR(12)	WSW wind during each month	%
DIR(13)	W wind during each month	%
DIR(14)	WNW wind during each month	%
DIR(15)	NW wind during each month	%
DIR(16)	NNW wind during each month	%

[a] From Williams et al. (1990b).

across a field, T is the time (sec) during which the wind exceeds the threshold velocity, and Y_{rw} is the wind erosion rate (kg/m/s) at time t. A stochastically generated wind speed distribution for each day is used to estimate the wind erosion rates. Initially, the percent of each day is determined for which a threshold wind speed is exceeded, above which wind erosion occurs. Then, the corresponding wind erosion rates are calculated for each erosive wind speed and integrated over 24 hourly time steps for the day.

Once the erosion rates have been determined, the wind erosion yield (Y_w) for the entire day is calculated by adjusting the potential erosion with the four factors given in equation 5. FI is a dimensionless factor based on the soil erodibility index developed by Woodruff and Siddoway (1965). The FR surface roughness factor is a function of both oriented roughness (ridges) formed by tillage operations (the effect of which changes according to wind direction), and roughness due to random cloudiness as determined by the shelter angle concept (Potter et al. 1990). The vegetative cover factor FV is calculated on a daily basis as a function of standing live biomass, standing dead residue, and flat crop residue. The estimation of the factor FD for the prevailing wind direction is performed as a function of field dimensions and wind direction.

B.5. Nitrogen cycling

Figure 3 shows the pools and flows simulated in the nitrogen (N) submodel of EPIC. Here, the main source of N to the soil system is via organic (manure) and inorganic fertilizer applications, which are specified in total equivalent N. If organic N is applied, the model assumes that it is subdivided between the fresh organic N, and the ammonia (NH_3) and/or mineral nitrate (NO_3-N) pool. The N in the ammonia pool is then available to be

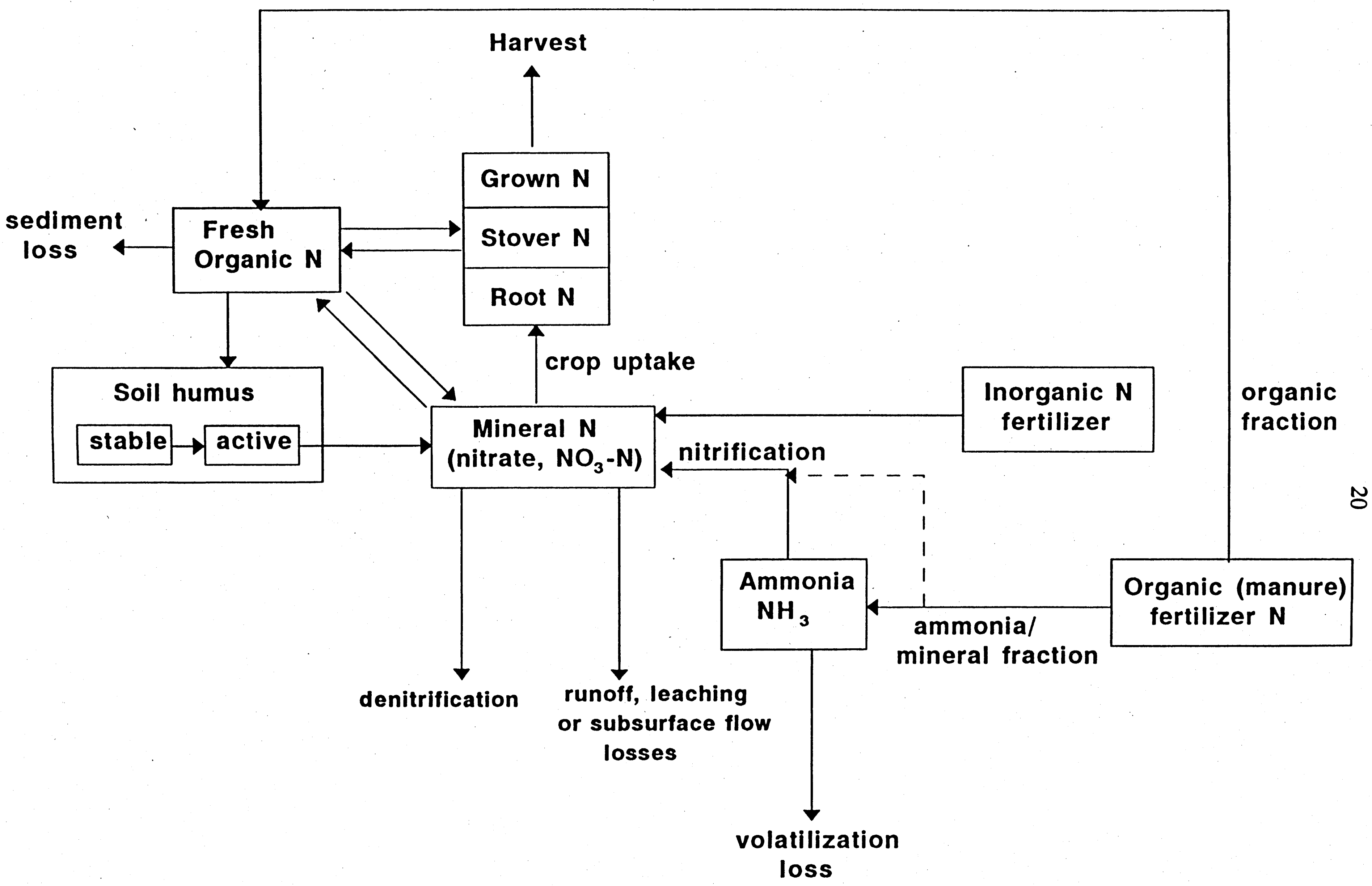

Figure 3. Pools and flows in the nitrogen submodel of EPIC; organic fertilizer N is partitioned into fresh organic and ammonia fractions (the latter of which can be partitioned between ammonia and/or nitrate)

volatilized to the atmosphere or to be converted into nitrate via nitrification. Inorganic N is assumed to be applied directly to the mineral NO_3-N pool. Input of N to the soil system is also supplied by rain, which is computed on a daily basis as the product of rainfall amount and concentration of N in the rain. An average N concentration is assumed for all storms at a given location.

The mineral N is available to be denitrified, taken up by the crop, immobilized to the fresh organic N, or lost in runoff, leaching, and/or subsurface flow. Denitrification is a microbial process that is modeled as a function of temperature and water content, and only occurs in EPIC when the soil water content is 95 percent of field capacity or greater. An exponential function based on temperature, organic carbon, and NO_3-N is used to estimate the denitrification rate.

For the top soil layer, runoff as well as percolation and subsurface flow losses of N are estimated. To determine N loss in runoff, an exponential function is first applied to calculate how much the NO_3-N concentration is reduced due to water flowing through the top layer. Then, the average daily NO_3-N concentration in runoff, percolation, and subsurface flow is determined by integrating over the exponential function, providing the NO_3-N yield, and then dividing the yield by the total volume of water in each of the three hydrologic components. The total mass of nitrate in each loss component is computed as the products of the average concentrations and the volume of water. In the lower layers, leaching and subsurface flow of nitrate are determined with the same approach. Upward movement of nitrate to the top soil layer via mass flow can occur when water is evaporating from the soil.

Organic N and soil organic matter in each soil layer are partitioned into two main pools, fresh organic matter and soil humus. An important source of N to the fresh organic pool is crop residue. Immobilization of N is calculated by subtracting the amount of N in the crop residue from the amount assimilated by microorganisms (which is estimated on the basis of carbon to nitrogen [C:N] ratios in each layer). This is an important process in EPIC because it determines the residue decomposition rate, which in turn has a direct effect on erosion.

A loading function is used to estimate the loss of organic N in sediment yield for the top soil layer. First, an enrichment ratio is used to determine the N concentration in the sediment yield. Then, the sediment yield is multiplied by the N concentration in the sediment and a constant to give the total mass of organic N lost in the sediment.

Mineralization of N is considered in EPIC for both the fresh organic N associated with the crop residue and microbial biomass, and the active pool of the soil humus. The rate of mineralization of the fresh organic N is regulated by C:N and C:P ratios, soil water, temperature and stage of residue decomposition. Mineralization of N in the soil humus active pool is estimated as a function of organic N mass, soil water, and temperature. Flow of N from the stable to the active pool is allowed to take place very slowly.

Crop uptake of N is governed by using a supply and demand approach. To estimate the daily N demand from the mineral pool, the product of biomass growth and optimal N concentration in the plant is computed. Optimal N concentration is estimated on the basis of the crop growth stage. The amount of N that is taken up by the crop is then constrained according to the amount of NO_3-N mass flow to the crop roots. The final amount of actual N uptake is determined by the minimum of supply and demand. Once the N is taken up by the plant, it is partitioned between the roots, aboveground biomass (shoots), and the fruit (yield). Biomass accumulation and leaf area expansion are affected by nitrogen deficiency factors that are computed as a function of actual, critical, and minimum shoot N concentrations.

Fixation of N by legumes is estimated as a fraction of daily plant N uptake during the period of the growing season when the crop is between 15 and 75 percent of maturity. If the root zone NO_3 content drops to 100 kg/ha/m, the fraction of daily plant N uptake fixed by the legume is allowed to go to 1.0. The fraction is also constrained by soil water content, and is set to 1.0 if the soil water content is 85 percent of field capacity. The fraction declines from 1.0 to 0.0 as the soil water content increases from 85 percent of field capacity to saturation (the entire soil pore space is filled with water), or as the soil water content declines from 85 percent of field capacity to wilting point.

B.6. Phosphorous cycling

A schematic of phosphorous (P) pools and flows simulated in EPIC is shown in Figure 4. When the P is first applied, it is labile (available for plant use). Transference of P to the active mineral pool can take place very quickly after entrance into the labile pool. At the same time, P moves from the active mineral pool back to the labile pool, normally at a much slower rate. The factors that control P movement between the labile and active mineral pools are soil water, temperature, a P sorption coefficient, and the amount of mineral in each pool. The flow of P between the active and stable mineral pools is simulated as a function of the P sorption coefficient and the concentration of P in each pool.

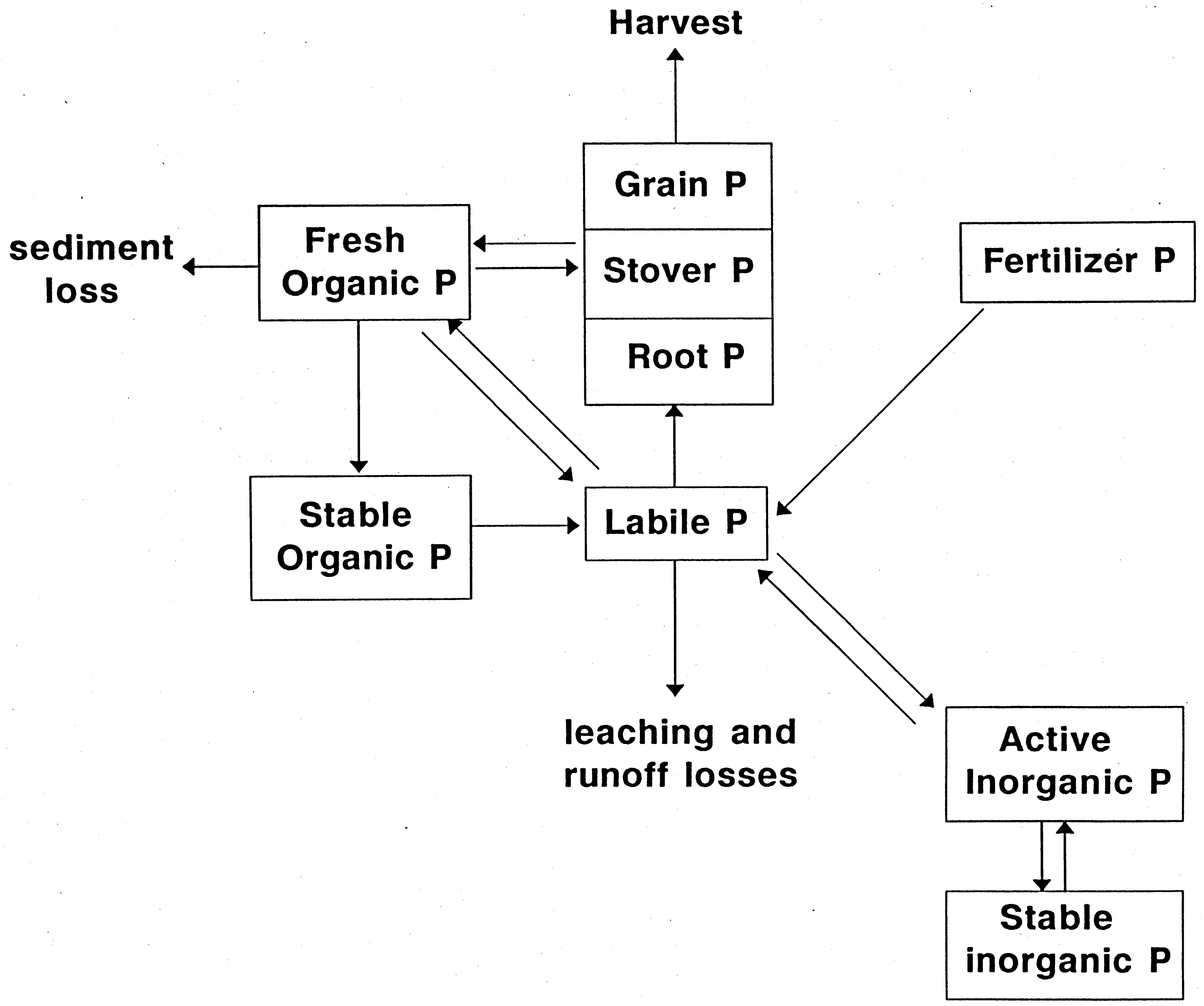

Figure 4. Pools and flows in the phosphorous submodel of EPIC

The P mineralization and immobilization models are similar in structure to those described for the N cycling submodel. Mineralization from the fresh organic P pool back to the labile pool is determined on the basis of the C:N and C:P ratios, soil water, temperature, and the stage of residue decomposition. Mineralization from the stable P pool to the labile pool is simulated as a function of organic P weight, labile P concentration, soil water, and temperature.

Soluble phase runoff of P is calculated for the top soil layer by using the labile P concentration, runoff volume, and a partitioning factor. Leaching of P below the root zone is removed from the labile pool. Loss of P on sediment (the dominant P loss pathway) from the fresh organic pool is simulated with a loading function similar to that used for N. A supply and demand approach for crop uptake of P from the labile pool is used, again similar to the method used for N. However, the P supply is estimated on the basis of plant demand, labile P concentration, and root mass.

B.7. Soil temperature

Calculation of the daily soil temperature at the center of each soil layer is then used within the nutrient cycling and hydrology routines. At the surface, the soil temperature is determined on the basis of the daily maximum and minimum air temperatures, and the snow, plant, and residue cover for the current day plus the previous four days. The soil surface temperature, a damping depth, and the mean annual air temperature are then used to calculate the soil temperature at the center of each sublayer. The damping depth is the soil depth at which the temperature remains virtually constant (at approximately the same value as the long-term average air temperature). It is determined as a function of bulk density and soil water.

B.8. Crop growth

A single crop growth model is used in EPIC to estimate the effects of erosion on soil productivity, which is expressed in terms of crop yield. Unique parameters are entered for each crop (Table 7) to simulate the development and yield of each crop. Processes simulated include leaf interception of solar radiation, conversion to biomass, division of biomass into roots, root growth, water use, nutrient uptake, aboveground biomass, and yield. A detailed description of the crop growth model, as well as comparisons of predicted yields with measured data for several crops, are described by Williams et al. (1989).

Phenological development of crops is simulated in EPIC by calculating accumulation of heat units (analogous to growing degree days) by

$$HU_k = \left[\frac{T_{mx,K} + T_{mn,K}}{2} \right] - T_b, \tag{9}$$

where HU, T_{mx}, T_{mn}, are the heat units, maximum temperature, and minimum temperature expressed in °C for day K, and T_b is the crop-specific base temperature in °C (growth does not occur at or below T_b). A heat unit index is then computed that affects several growth processes including leaf area development and senescence (decline), optimum plant nutrient concentrations, partition of biomass between roots, shoots (aboveground biomass), and yield, and the harvest date. The harvest unit index is calculated as

Table 7. EPIC crop data inputs[a]

Variable	Definition	Units
CPNM	Crop name (up to 4 characters)	---
WA	Biomass energy ratio	t ha^{-1} MJ^{-1}
HI	Harvest index	kg kg^{-2}
TB	Optimal temperature for plant growth	°C
TG	Minimum temperature for plant growth	°C
DMLA	Maximum potential leaf area index	---
DLAI	Fraction of growing season when leaf area starts declining	---
DLAP(1,2)	Two points on optimal leaf area development curve	%
RLAD	Leaf area index decline rate parameter	---
RBMD	Biomass-energy ratio decline rate parameter	---
ALT	Aluminum tolerance index	
CAF	Critical aeration factor	---
SDW	Seeding rate	ka ha^{-1}
HMX	Maximum crop height	m
RDMX	Maximum root depth	m
CVM	Maximum value of C factor for water erosion	---
CNY	Fraction of nitrogen in yield	kg kg^{-1}
CPY	Fraction of phosphorus in yield	kg kg^{-1}
WSYF	Water stress—crop yield factor	---
PST	Pest (insects, weeds, and disease) factor	---
COSD	Seed cost	\$ kg^{-1}
PRY	Price for yield	\$ t^{-1}
WCY	Fraction water in yield	---
BN_1,BN_2,BN_3	Nitrogen uptake parameters at emergence, mid-season, and maturity	---
BP_1,BP_2,BP_3	Phosphorus uptake parameters at emergence, mid-season, and maturity	---
BW_1,BW_2,BW_3	Wind erosion parameters for standing live biomass, standing dead crop residue, and flat residue	---
IDC	Crop category number[b]	---
FRST(1,2)	Two points on frost damage curve	°C

[a] From Wiiliams et al. (1990b).

[b] Crop category numbers: 1 - warm season annual legume, 2 - cold season annual legumes, 3 - perennial legume, 4 - warm season annual, 5 - cold season annual, 6 - perennial, 7 - trees

$$HUI_i = \frac{\left[\sum_{k=1}^{i}\right] HU_k}{PHU_j}, \tag{10}$$

where HUI is the heat unit index for day i and PHU is the potential heat units required for a specific crop j to reach maturity. The PHU value is either input by the user or calculated internally by the model based on the planting and harvesting dates (note that EPIC assumes that maturity is synonymous with harvest date).

Crop interception of solar radiation is simulated with the Beer's law equation (Monsi and Saeki 1953)

$$PAR_i = 0.5(RA)_i[1-e^{(-0.65LAI)}]_i, \tag{11}$$

where PAR and RA are the intercepted photosynthetic active radiation and solar radiation in MJ/m^2, LAI is the leaf area index, and i is the day of the year. The potential daily increase of biomass is determined with the following expression as given by Monteith (1977):

$$\Delta B_{p,i} = 0.001 \ (WA)_j(PAR)_j(1 \ + \ \Delta HLRT_i)^3 \tag{12}$$

where ΔB_p is the daily potential biomass increase (t/ha), WA is the crop parameter for converting energy to biomass (t/ha*MJ), HLRT is the day length (hr), and $\Delta HLRT$ the change in day length (hr/day).

The LAI is the measure of unit leaf area per unit of ground area and is calculated as a function of heat units, the maximum leaf area index crop input parameter, a crop parameter that initiates leaf area decline, and crop stress factors. An example of a sigmoidal curve used to define leaf area development with crop parameters DLAP1 and DLAP2 (see Table 7) set to 15.01 and 50.95 is shown in Figure 5. The number to the left of the decimal for

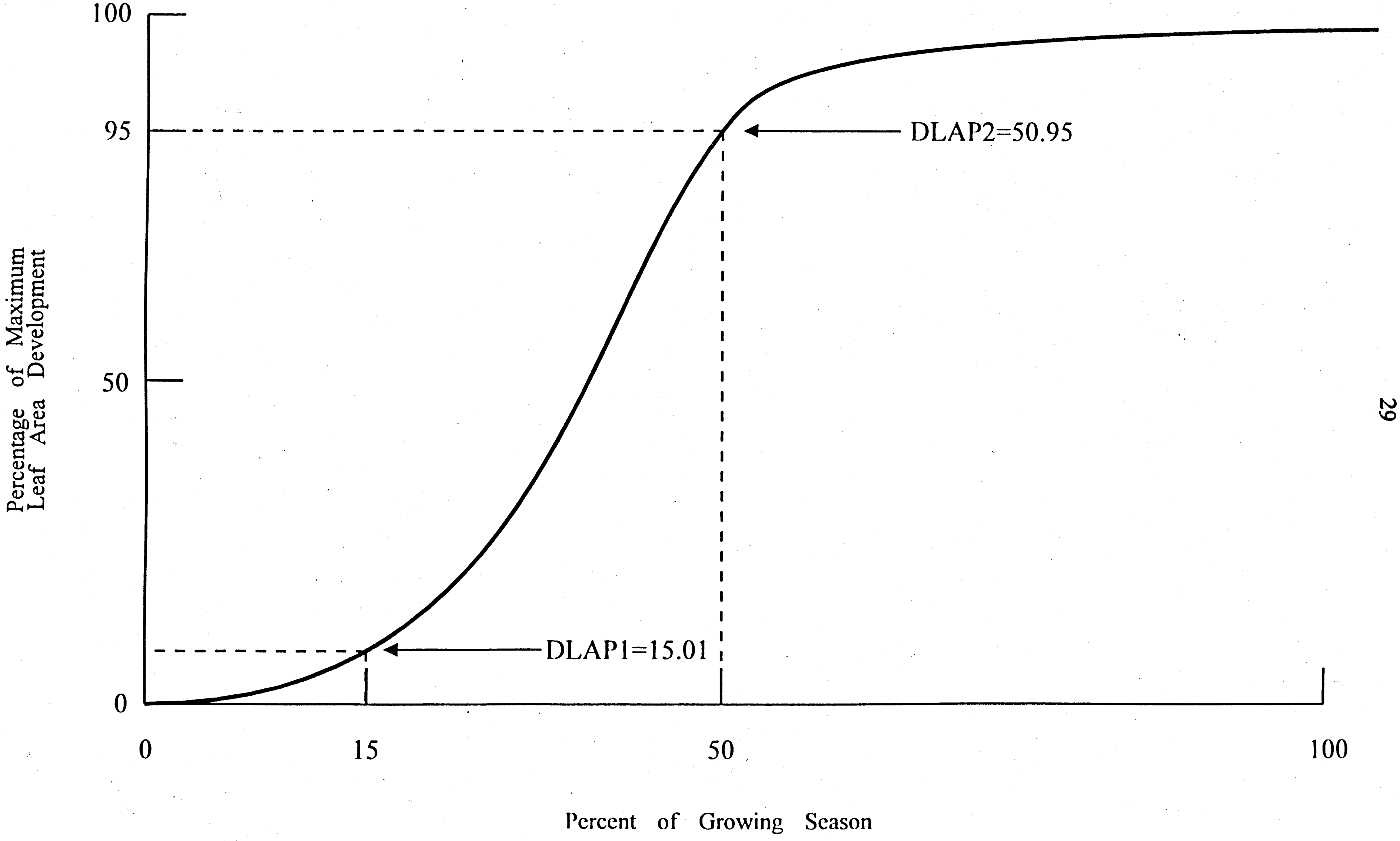

Figure 5. Example of typical sigmoidal curve used in EPIC to relate percent maximum leaf area development to percent of growing season when DLP1 and DLP2 are set to 15.01 and 50.95, respectively (from Dumesnil 1992).

the two parameters is the percentage of the growing season (based on accumulated heat units); the number to the right of the decimal is the percentage of maximum leaf area growth. The point in the growing season where leaf area decline begins, due to leaf senescence as a crop approaches physiological maturity, is controlled by the crop parameter DLAI and is shown in Figure 6. The rate of leaf area decline is linear if the crop parameter RLAD equals 1.0, is initially slow and then rapidly increases if RLAD is less than 1.0 , and is initially fast and then slows if RLAD is greater than 1.0. In all cases the LAI approaches zero at maturity.

Four plant stress factors (water, temperature, nutrient, and, aeration) that range from 0.0 to 1.0 are used in EPIC to adjust the daily potential biomass. If any of these factors is below 1.0, the estimated potential biomass is multiplied by the stress factor to perform the adjustment. If more than one factor is below 1.0, the minimum value is used. Root growth is constrained by either the soil strength, temperature (stress), or aluminum toxicity, depending on which factor is the most limiting.

Root growth is simulated linearly by partitioning 40 percent of the daily biomass growth at emergence and 20 percent at maturity to the roots. Within each soil layer, the root weight is calculated on the basis of plant water use within that layer. Root depth is assumed to increase linearly as a function of heat units and potential root zone depth. If water deficits exist in some soil layers, the roots are allowed to draw additional water from layers that contain adequate supplies in order to compensate for the deficit (depending on limitations governed by the root growth stress factor).

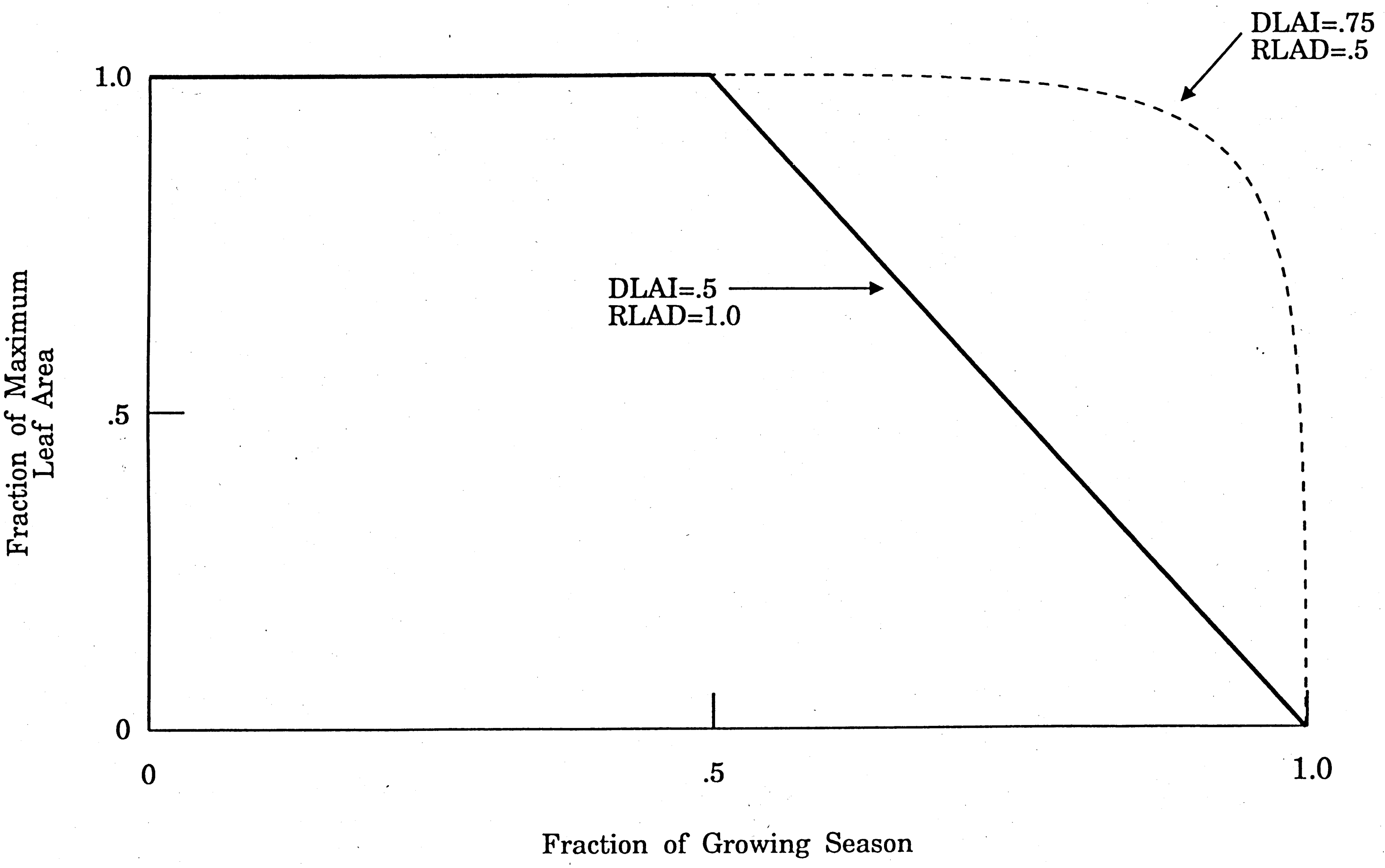

Figure 6. Example of leaf area decline in EPIC as the crop approaches physiological maturity with DLAI set to 0.5 and RLAD equal to 1.0 (from Dumesnil 1992).

Crop yield is determined with a harvest index that increases nonlinearly from zero heat units at planting to the optimal heat unit value at maturity. The harvest index is adjusted on the basis of any water stress that occurs during critical crop stages that normally take place sometime between 30 and 90 percent of maturity. The final yield is determined by multiplying the aboveground biomass by the adjusted harvest index.

B.9. Tillage

Specific tillage implements are simulated in EPIC to account for the impact of different tillage levels on erosion and soil productivity. The tillage implement identification number, as well as the month and day of the operation, must be entered into the model as shown in Table 8 (this holds true for other operations as well). A curve number (CN) can also be entered for each tillage operation if desired. Specific parameters (Table 9) are provided with a machinery table (Table 10) in order to simulate the mixing efficiency of residue on the surface, tillage depth, and other processes associated with each piece of equipment (the abbreviated equipment names are defined in Table 11). Values are set to 0.0 for those parameters that do not apply for the individual tillage implement. Mixing of nutrients and crop residue within the plow depth, changes in bulk density, and conversion of standing crop residue to flat residue are simulated in the tillage submodel. Simulation of ridge height and surface roughness are also performed.

Conversion of standing residue to flat residue by a tillage operation is accomplished with an exponential function of tillage depth and mixing efficiency. A portion of the residue, equivalent to the mixing efficiency, is mixed uniformly within the plow depth when the tillage

Table 8. Selected Management data inputs[a]

Variable	Definition	Units
NRO	Crop rotation duration[b]	yr
IRR	Irrigation code (dryland; sprinkler; or furrow)	---
IRI	Minimum application interval for automatic irrigation	d
IFA	Minimum fertilizer application interval for automatic option	d
LM	Liming code	---
IFD	Furrow dike code	---
IDR	Drainage code	---
MO	Month of irrigation application	---
IDA	Day of month of irrigation application	---
VIRR	Irrigation volume	mm
MO	Month of fertilizer application	---
IDA	Day of month fertilizer application	---
FN	Nitrogen fertilizer applied	kg ha^{-1}
FP	Phosphorus fertilizer applied	kg ha^{-1}
FDP	Depth of fertilizer placement	mm
MT	Month of tillage operation	---
IT	Day of month of tillage	---
LT	Tillage operation identification number	---
J2	For tree crops only	yr
PHU	Potential heat units	C
CN2	Runoff curve number	---

[a] From Williams et al. (1990b).

[b] Up to 30-year rotations can be simulated.

Table 9. Definition of tillage parameters[a]

Variables	Definitions	Units
TIL	Equipment name (up to 8 characters, beginning in column 1)	---
COTL	Cost of operation	$\$ ha^{-1}$
EMX	Mixing efficiency of operation	---
RR	Surface random roughness created by operation	mm
TLD	Tillage depth (positive depth is below the surface; negative indicates above ground cutting height)	mm
RHT	Ridge height	mm
RIN	Ridge interval	m
DKH	Furrow dike height	mm
DKI	Furrow dike interval	m
IHC	Operation code[b]	---
HE	Harvest efficiency	---
ORHI	Override of harvest index (HI)	---

[a] From Williams et al. (1990b).

[b] Operation codes: 6-plants with drill; 5-plants in rows; 2-harvests without killing the crop; 1-harvests and kills the crop; -1-builds furrow dikes; -2-destroys furrow dikes.

Table 10. Tillage implement and associated parameters table provided with EPIC[a,b]

Tillage implement name	Number[c]	COTL ($/HA)	EMX	RR (mm)	TLD (mm)	RHT (mm)	RIN (m)	DKH (mm)	DKI (m)	IHC	HE	ORHI
LISTRPLT	1	.00	.15	10.00	40.00	75.00	1.00	.00	.00	5.00	.00	.00
ROW PLT	2	.00	.05	5.00	60.00	10.00	.86	.00	.00	5.00	.00	.00
PLANT DR	3	.00	.25	10.00	40.00	25.00	.17	.00	.00	6.00	.00	.00
TRSPLANT	4	.00	.15	10.00	500.00	75.00	1.00	.00	.00	5.00	.00	.00
INJ-PEST	6	.00	.00	.00	75.00	.00	.00	.00	.00	7.00	.00	.00
IRSTRSCH	9	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
SPREADER	10	.00	.00	.00	.00	.00	.00	.00	.00	4.00	.00	.00
SPRAYER	11	.00	.00	.00	.00	.00	.00	.00	.00	7.00	.95	.00
ANHYD AP	12	.00	.15	13.00	75.00	25.00	.30	.00	.00	4.00	.00	.00
LISTER	15	.00	.80	25.00	100.00	150.00	1.00	.00	.00	.00	.00	.00
DISK BED	16	.00	.70	.00	100.00	75.00	1.00	.00	.00	.00	.00	.00
ROWBUILD	17	.00	.50	15.00	350.00	300.00	1.78	.00	.00	.00	.00	.00
CULTPACK	18	.00	.10	5.00	40.00	25.00	1.78	.00	.00	.00	.00	.00
ROW CULT	19	.00	.30	15.00	25.00	100.00	1.00	.00	.00	.00	.00	.00
FLD CULT	20	.00	.30	6.00	50.00	25.00	.25	.00	.00	.00	.00	.00
ROT HOE	21	.00	.10	13.00	5.00	.00	.00	.00	.00	.00	.00	.00
ROD WEED	22	.00	.05	10.00	25.00	.00	.00	.00	.00	.00	.00	.00
SWEEP	23	.00	.30	15.00	75.00	.00	.00	.00	.00	.00	.00	.00
NOBLE PL	24	.00	.10	15.00	100.00	.00	.00	.00	.00	.00	.00	.00

Table 10. (Continued)

SAND F	26	.00	.10	20.00	15.00	.00	.00	.00	.00	.00	.00	.00
MB PLOW	28	.00	.90	30.00	150.00	.00	.00	.00	.00	.00	.00	.00
TAN DISK	29	.00	.50	18.00	75.00	.00	.00	.00	.00	.00	.00	.00
PT-CHS	30	.00	.37	20.00	150.00	50.00	.30	.00	.00	.00	.00	.00
TWPT-CHS	31	.00	.42	25.00	150.00	75.00	.30	.00	.00	.00	.00	.00
SWP-CHS	32	.00	.33	20.00	100.00	25.00	.30	.00	.00	.00	.00	.00
OFFSET-D	33	.00	.75	50.00	100.00	.00	.00	.00	.00	.00	.00	.00
SUBSOIL	34	.00	.20	15.00	350.00	.00	.00	.00	.00	.00	.00	.00
KILL	41	.00	.00	.00	.00	.00	.00	.00	.00	1.00	.00	.00
HARV2.95	51	.00	.00	.00	-100.00	.00	.00	.00	.00	2.00	.95	.00
HARVOR85	52	.00	.00	.00	-150.00	.00	.00	.00	.00	2.00	.95	.85
HARVOR95	53	.00	.00	.00	-50.00	.00	.00	.00	.00	2.00	.95	.95
SWATHER	54	.00	.00	.00	-150.00	.00	.00	.00	.00	2.00	.45	.75
BALER	55	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
PNUT DIG	56	.00	.50	20.00	180.00	.00	.00	.00	.00	2.00	.95	.00
SHREDDER	57	.00	.00	.00	-75.00	.00	.00	.00	.00	.00	.00	.00
BURNED	58	.00	.00	.00	-10.00	.00	.00	.00	.00	.00	.00	.00
CLEARCUT	59	.00	.00	.00	.00	.00	.00	.00	.00	2.00	1.00	.76
BAGMOWER	60	.00	.00	.00	-60.00	.00	.00	.00	.00	2.00	.80	.50
MULCHMOW	61	.00	.00	.00	-60.00	.00	.00	.00	.00	2.00	.01	.50
GRAZE1	65	.00	.00	.00	-50.00	.00	.00	.00	.00	2.00	.15	50.00

Table 10. (Continued)

GRAZE2	66	.00	.00	.00	-100.00	.00	.00	.00	.00	2.00	.10	5.00
GRZ2-AUM	67	.00	.00	.00	-50.00	.00	.00	.00	.00	2.00	.05	50.00
GRZ1-AUM	68	.00	.00	.00	-50.00	.00	.00	.00	.00	2.00	.05	25.00
FERTILIZE	71	.00	.00	.00	.00	.00	.00	.00	.00	4.00	.00	.00
IRRIGATE	72	.00	.00	.00	.00	.00	.00	.00	.00	3.00	.00	.00
BDIKE100	75	.00	.70	10.00	40.00	100.00	1.00	100.00	10.00	-1.00	.00	.00
BDIKE300	76	.00	.70	10.00	40.00	100.00	1.00	300.00	10.00	-1.00	.00	.00
RMV-DIKE	77	.00	.70	10.00	40.00	100.00	1.00	.00	.00	-2.00	.00	.00
BDIKE100	78	.00	.70	10.00	40.00	100.00	.25	100.00	.40	-1.00	.00	.00
PADDYBD	80	.00	.00	.00	100.00	1000.00	100.00	1000.00	200.00	-1.00	.00	.00

[a] From Dumesnil (1992).

[b] See Table 9 for definitions of parameters; see Table 11 for definitions of the tillage implements.

[c] Number refers to tillage implement identification code in EPIC.

Table 11. Definitions of abbreviated tillage implement names listed in Table 10 [a]

Tillage implement name	Definition
LISTRPLT	Lister planter
ROW PLT	Row planter
PLANT DR	Drill planter
TRSPLANT	Transplanter for trees
INJ-PEST	Inject pesticide
IRSTRSCH	This is a false tillage operation. It does not disturb the soil, harvest, or plant. It is used only when the plant or soil water stress levels needed to trigger automatic irrigation are changed during the year or rotation.
SPREADER	Used to apply fertilizer
SPRAYER	Used to apply pesticides
ANHYD AP	Anhydrous ammonia applicator
LISTER	Lister
DISK BED	Disk bedder
ROWBUILD	Row builder for sugar cane
CULTPACK	Culti-packer
ROW CULT	Row cultivator
FLD DULT	Field cultivator
ROT HOE	Rotary hoe
ROD WEED	Rod weeder
SWEEP	Sweep
NOBLE PL	Noble plow
SPIK HAR	Spike harrow
SAND F	Sand fighter - for wind erosion control
MB PLOW	Mold board plow
TAN DISK	Tandom disk
PT-CHS	Point chisel
TWPT-CHS	Twisted point chisel
SWP-CHS	Sweep chisel
OFFSET-D	Offset disk
SUBSOIL	Deep tillage device

Table 11. (Continued)

KILL	Use after harvest to kill crop
Tillage implement name	Definition
HARV2.95	Harvest with 95% efficiency - does not kill crop
HARVOR85	Harvest with 95% efficiency - does not kill crop Harvest index override 85% - used for forage crop
HARVOR95	Harvest with 95% efficiency - does not kill crop Harvest index override 95% - used for forage crop
SWATHER	Harvests but does not kill the crop
BALER	Baler for hay or crop residue
P NUT DIG	Peanut digger
SHREDDER	Shredder
BURNED	Burning operation - does not kill crop
CLEARCUT	Harvests trees in a clearcut operation
BAGMOWER	Bagmower
MULCHMOW	Mulchmower
GRAZE1	Cattle grazing - 50 kg of biomass removed per day
GRAZE2	Cattle grazing - 5 kg of biomass removed per day
GRZ2-AUM	25 kg consumed and 25 kg trampled, daily; feed conversion 10 to 1
GRZ1-AUM	12.5 kg consumed and 12.5 kg trampled, daily; feed conversion 10 to 1
FERTILIZE	Applies user-specified dates and amounts of fertilizer
IRRIGATE	Applies user-specified dates and amounts of irrigation
BDIKE100	Implement that builds 100 mm tall furrow dikes
BDIKE300	Implement that builds 300 mm tall furrow dikes
RMV-DIKE	Removes furrow dikes
PADDYBD	Rice paddy simulation - builds paddy border

[a] From Dumesnil (1992).

operation is performed. At the same time, the bulk density is reduced on the basis of mixing efficiency, bulk density before tillage, and undisturbed bulk density. Following the tillage pass, the bulk density is allowed to return to the previous undisturbed value at a rate dependent upon water infiltration, tillage depth, and soil texture.

B.10. Plant environment control

The plant environment control subcomponent provides the means for application of irrigation water, fertilizer, lime, and pesticides, or for simulating a drainage system. Important input variables used for these different management options are listed in Table 8.

Sprinkler or furrow irrigation can be simulated in EPIC on either an automated basis or by specifying the exact dates and rates for irrigation water to be applied. If the automatic option is chosen, the user inputs a plant water stress level to trigger each irrigation application, the maximum volume of irrigation water that can be applied in each growing season, and the minimum time interval between applications. Irrigated crops are not being considered for the analysis of GRIP and NISA.

Fertilizer applications can also be specified by the user or set in an automatic mode. The N and P application dates, rates, and depths are all input if the automatic option is not chosen. If the automatic option is selected, the model decides when and how much fertilizer should be applied. First, a soil sample is taken at planting time to determine how much N and P should be applied to bring the root zone concentrations up to the level that existed at the start of the simulation. Then, if N is the limiting crop growth constraint, further N applications are made during the growing season. Required inputs for the automatic option include a plant stress level to trigger N application, the maximum (total) N application over the entire growing season, and the minimum number of days between N applications.

Application of lime can be simulated in EPIC to neutralize acidity resulting from either toxic levels of extractable aluminum in the plow layer or from ammonia-based fertilizers. The required amount of lime is applied and incorporated into the plow layer when the sum of acidity due to extractable aluminum and fertilizer exceeds 4 t/ha.

The final two plant environment control options are drainage and furrow diking. The natural lateral subsurface flow of a soil is modified in order to account for drainage. First, the soil layer that has the drainage system needs to be specified. Then, the amount of time needed for the drainage system to reduce plant stress is indicated. Furrow dikes are small temporary dikes that are constructed across furrows to conserve water for crop production. Because they reduce runoff, they may also be effective in limiting erosion. Furrow dikes can be accommodated in EPIC for any combination of inputed ridge spacing and interval down the furrows (see Tables 8, 9, and 10) . Mechanized construction or destruction of the dikes can be simulated on any day of the year. If the runoff for an individual storm event does not exceed the dike storage volume, then all the rain infiltrates and can be potentially used by the crop. Otherwise, "overtopping" occurs and it is assumed that all of the runoff is lost. If the dikes are destroyed by a runoff event, the model automatically rebuilds them. Examples of furrow diking can be found in Krishna et al. (1987) and Williams et al. (1990a).

B.11. Pesticide fate

Pesticide fate routines from the Groundwater Loading Effects of Agricultural Systems (GLEAMS) model (Leonard et al. 1987) have been incorporated into EPIC (Sabbagh et al.

1991b). Multiple pesticide applications can be simulated for a single crop and growing season. The required inputs for each pesticide application include: (1) a tillage implement that carries a pesticide operation code, (2) the application date, (3) the application rate of the pesticide active ingredient (kg/ha), (4) the pest control factor (described below), and (5) the pesticide ID number.

The pesticide ID number links the application to a table supplied with the model that contains the following required chemical property inputs: (1) solubility (mg/l), (2) partition coefficient or K_{oc}, (3) soil half-life (days), (4) foliar half-life (days), and (5) wash-off fraction. The foliar half-life and the wash-off fraction are used only if the simulated pesticide is applied to the crop. Pesticide outputs include the amount leached below the root zone, edge-of-field losses in subsurface flow, edge-of-field runoff losses in both the solution phase and on eroded sediment, and the amount degraded on the crop and in the soil.

The effect of the applied pesticide on the target pests (insects, weeds, or diseases) and ultimately crop yield is handled indirectly in EPIC by using a pest control factor. This factor interacts with a generic pest damage factor that reduces the crop harvest index by assuming that pest damage increases as moisture, temperature, and residue increase. The amount of damage is constrained by the maximum harvest index reduction specified in the crop parameter set. The pest factor ranges from 0 to 1, where 1 indicates total pest control and no resulting damage to the crop. The pest factor is included in the variables listed for the crop parameters in Table 7.

B.12. Economic budgets

A crop budget and accounting system can be used in EPIC to track production and marketing costs. Both fixed and variable costs can be inputted. Fixed costs include depreciation, interest or return on investment, insurance, and taxes on land, equipment, and capital improvements (such as terraces, and drainage). Machinery repairs, fuel and other energy, machine lubricants, labor, seed, irrigation water, pesticide, and fertilizer are the variable cost inputs. Tillage and other preharvest operation costs must be calculated prior to model execution with a budget generator program such as the Micro Budget Management System (MBMS) (McGrann et al. 1986). Cost tracking is performed annually; tracking of costs is performed on an annual basis; all cost variables are set back to zero after harvest.

The EPIC budget generator and accounting system will not be used for this study because CRAM is being used to assess economic outcomes of the different policy scenarios.

III. DEVELOPMENT OF THE ENVIRONMENTAL DATABASE

A key task in constructing the integrated modelling system is the development of an environmental database that can be readily accessed by the environmental component of the system. The two major categories of data that must be assembled for the environmental component are the soil layer and landform database and the weather database. The required soil, landform, and weather data have been received and processed (Table 12). The steps taken to process these data into the final soil layer and landform database and the weather database are covered in the following discussion.

In conjunction with these databases, an automatic input file builder written in the C programming language is being constructed to facilitate the process of developing

Table 12. Required data for EPIC and current status of data at CARD

Required data	Data Components	Intended Application	Status
ARA Database weather data for AL, SK, and MN[a]	• 31-year (1955-85) historical daily weather files • 30-year climate normals (1951-80)	• EPIC calibration runs • Construction of EPIC weather generator files using daily data and solar radiation normals	Received; weather generator files have been processed
Other ARA Database files[a]	Soil moisture, land use, soil temperature, and other data for AL, SK, and MN	EPIC calibration runs	Received
AL wind speed and direction data[b]	Average monthly wind speeds and directional components	EPIC wind erosion submodel	Received in EPIC format
SK and MN wind speed and direction data[c]	"	"	Received, have been processed
Relative humidity data for AL, SK, and MN[c]	30-year climate normals for relative humidity	EPIC weather generater files	Received, have been processed
CanSIS soil landscape database for AL, SK, and MN[d]	Soil slope and other landform properties at the landscape polygon level	EPIC soil landform inputs	Received, have been processed
Soil layer data for AL[e]	Representative soils for specific ARAs	EPIC soil layer inputs	"
Soil layer data for SK[f]	Cultivated soils across entire province	"	"
Soil layer data for MN[g]	Representative soils for specific ARAS	"	"

Table 12. (Continued)

Required data	Data Components	Intended Application	Status
Cross-match files[a] for AL, SK, and MN	Link soil landscape polygons to ARAs	Construct soil files for EPIC	Received
Elevation data[a]	Average elevation for each ARA	Required for Perman-Monteith evapotranspiration routine in EPIC	Received
Data for 6 sites in Manitoba[h]	• Historical daily weather data for nearest weather stations • Management, yield, soil, and simulated erosion data for each site	EPIC calibration runs	Received
Swift Current, Saskatchewan rotation data[i]	• Long-term crop rotation data • Management, soil, and weather data	"	Received
Slope lengths for AL,[e] SK[f] and MN[j]	Estimated slope length values for different local surface forms	Required for water erosion calculations in EPIC	Received
AL, SK, and MN management and cropping systems[k]	"	"	"

[a] Kirkwood, V. Centre for Land and Biological Resource Research, Agriculture Canada, Ottawa, Ontario.

[b] Tautchin, M. Alberta Agriculture, Conservation and Development Branch, Edmonton, Alberta.

[c] Teeter, G. Climate Centre, Climate Information Branch, Atmospheric Environment Service, Downsview, Ontario.

[d] Schut, P. Centre for Land and Biological Resource Research, Agriculture Canada, Ottawa, Ontario.

[e] Tajek, J. Alberta Agriculture, Edmonton, Alberta.

[f] Padbury, G. Agriculture Canada Research Branch, Saskatoon, Saskatchewan.

[g] Fraser, W. Centre for Land and Biological Resources Research, Manitoba Land Resource Unit, University of Manitoba, Winnipeg, Manitoba.

[h] Sheykawich, C. Department of Soil Science, University of Manitoba, Winnipeg, Manitoba.

[i] Zentner, R. Agriculture Canada Research Station, Swift Current, Saskatchewan.

[j] Coote, D. Centre for Land and Biological Resource Research, Agriculture Canada, Ottawa, Ontario.

[k] Izaurralde, C. Department of Soil Science, University of Alberta, Edmonton, Alberta.

metamodels with EPIC. The soil layer and landform data have been linked with the aid of Paradox©, a relational database, so that the soil data can be provided in a standard format for all three provinces to the input file builder. The input file builder will greatly simplify the process of constructing the thousands of input files required for the analysis and will allow quicker mass production than that provided by UTIL.

A. Development of the Soil Layer and Landform Database

Two categories of soil information are required for EPIC: (1) layered properties of the soil profile and (2) landform characteristics defined primarily by land surface slope and slope length. In addition, the area of each soil for each ARA is required to assign weights for aggregation of erosion rates and other environmental indicators to the CRAM region level. Table 13 lists the five types of raw data sets provided to develop the soil layer and landform database for EPIC. Soil layer data can be used at either an ARA or landscape polygon level (see definitions in Table 14). However, the landform data provided from the CanSIS Landscape Database (Shields et al. 1991) exist only at the landscape polygon level. This is an important distinction because the land surface slope and slope length values for a given soil, which are essential for estimating water erosion with the USLE equation in EPIC, often change between polygons, resulting in several "new soils" for a single soil code that has static layer properties. Thus, a modified strategy of estimating erosion rates and other environmental indicators at the ARA level must be used by executing EPIC at the landscape polygon level and subsequently aggregating the results to the ARA level.

Table 13. Description of initial (raw) datasets used to construct the soil

File	Description
Soil layer (SL) data	Contains soil layer properties for depths down to 1.0-2.0 m for selected soils in each providence.
Landscape database (LD) dominant	Landform and other information for the dominant soils in each landscape polygon.
Landscape database (LD) subdominant	Landform and other information for the subdominant soils in each landscape polygon.
ARA-landscape polygon (ARA-LP) cross-match	Link landscape polygons to the ARAs in which they reside.
ARA area	Contain the areas of each of the agriculturally significant ARAs.

Table 14. Definition of agroecological resource areas (ARAs) and landscape polygons

Region type	Definition
ARA[a]	A natural landscape unit that possesses relatively uniform agro-climate, land form, soils, and general agricultural potential at the 1:2 million scale. ARAs vary in size from under 100,000 ha to over 1,000,000 ha.
Landscape Polygon[b]	A natural landscape unit that is cahracterized by unique combinations of soils, landforms, and parent materials at the 1:1 million scale. Dominant soil landscapes represent at least 40 percent of a polygon while subdominant landscapes represents 16 to 40 percent of a polygon. Typically, several landscape polygons exist within an ARA.

[a] Based on information given by Hiley and Wehrhahn (1991) and from Dumanski (1993).

[b] Based on information given in Shields et al. (1991).

Table 15 lists by province the total records, ARAs, landscape polygons, and unique soil codes for each of the file types listed in Table 13. The landscape database contains many additional landscape polygons as compared to the ARA-LP cross-match files for the areas of each province that lie outside of the regions that have been defined by ARAs. For Alberta, three times as many records exist as landscape polygons because polygons can cross ARA boundaries, with the dual results that: (1) a given polygon can exist in several ARAs and (2) multiple pieces of a polygon can exist independently within the same ARA. These multiple pieces were summed within each ARA to arrive at a single ARA-polygon area, reducing the total number of records for the Alberta cross-match file to 1,608. It should also be noted that only 80 ARAs are included in the Alberta area file because these are the principal agricultural ARAs in the province. The soil layer data provided includes the entire cultivated soil data set for Saskatchewan, and preselected subsets of the Alberta and Manitoba cultivated soils that represent the major agricultural soils of each ARA in the two provinces.

A schematic of the required steps to process and merge the data into the final EPIC soil layer and landform files is shown in Figure 7. The core of the procedure is to link acreages, soil layer data, LS factors, and landform information by soil code, ARA, and landscape polygon. As a part of this procedure the soil layer data are transformed into the proper EPIC format, and slope lengths and hydrologic groups are calculated for each soil (see sections III.B.2.-4. for a description of these steps). The overall procedure is repeated three times to create separate data sets for each province.

Table 15. Total number of records, ARAs, landscape polygons, and unique soil codes by province for the files described in Table 1[a]

Province	File	Total records	ARAs	Landscape polygon codes	Unique soil codes
Alberta	SL data	627	-	-	120
	LD dominant	894	-	894	141
	LD subdominant	894	-	894	170
	ARA-LP cross-match[b]	2,247	99	716	-
	ARA area	80	80	-	-
Manitoba	SL data	253	-	-	59
	LD dominant	817	-	817	159
	LD subdominant	817	-	817	150
	ARA-LP cross-match	249	63	249	-
	ARA area	63	63	-	-
Saskatchewan	SL data	1,658	-	-	520
	LD dominant	1,875	-	1,875	166
	LD subdominant	1,875	-	1,875	177
	ARA-LP cross-match	941	118	941	-
	ARA area	118	118	-	-

[a] A "-" indicates that no information is available for the data category.

[b] Landscape polygon boundaries cross ARA boundaries in Alberta, resulting in situations where a polygon exists in more than one ARA and/or where "pieces" of a polygon show up several times in an ARA. Thus, there are over three times as many records as landscape polygons in Alberta. When the polygon pieces are summed to a single area within a given ARA, the total records are reduced to 1,608.

[c] Many of the soil codes that are in the LD dominant files are also in the LD subdominant files.

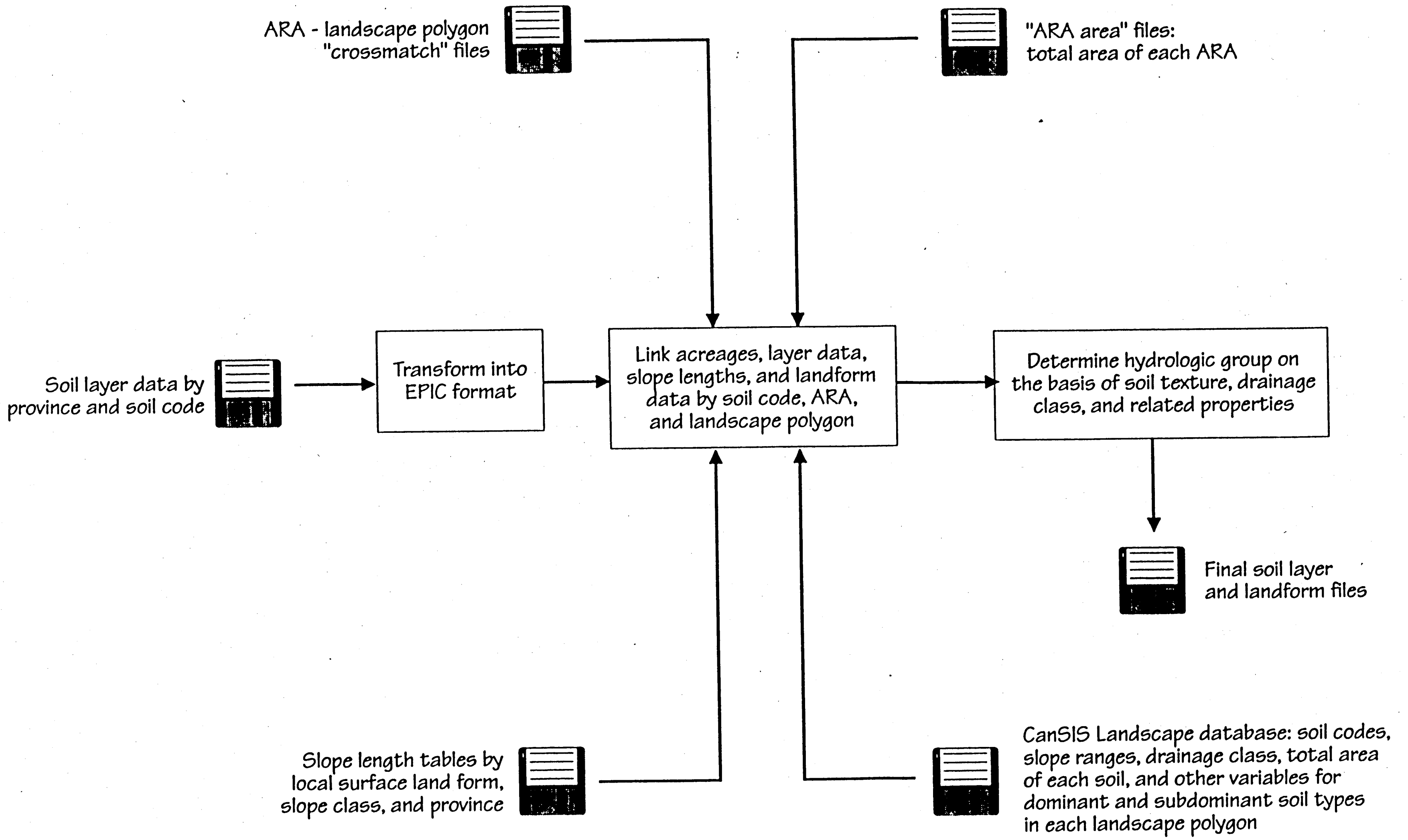

Figure 7. Development of EPIC soil layer and landform data for Alberta, Saskatchewan, and Manitoba

Table 16 lists by province a summary of the total ARAs, landscape polygons, and soil codes in the final data sets after linking the different files, as shown in Figure 7. In the process of merging the files, a number of ARAs, landscape polygons, and soil codes were dropped (lost) from the original raw data sets. As already noted for Alberta, only 80 of the 99 ARAs are considered to be agriculturally important, resulting in the other 19 being dropped. For Manitoba, 19 of the 23 ARAs dropped were identified as containing no agricultural soils in information received with the soil layer data sent by the Centre for Land and Biological Resource Research in Winnipeg. Further queries of the data revealed that all the landscape polygons in the other dropped Manitoba ARAs are dominated by forest or some other nonagricultural vegetation. Although the exact characteristics of the 12 ARAs dropped for Saskatchewan have not been determined, it is likely that they are also relatively agriculturally insignificant.

Obviously, those landscape polygons that exist within the dropped ARAs must also be excluded. In addition, many other polygons were dropped because neither the dominant nor subdominant soil code of the polygon could be matched to a soil code in the respective soil layer data. Likewise, soils dropped from the soil layer data files are those that could not be matched to a single dominant or subdominant soil of at least one polygon within the province. While it is probable that many of the dropped polygons are predominantly nonagricultural, it is possible that some significant agricultural polygons were also excluded.

Table 16. Summary of ARA, landscape polygon, and soil code totals after merging the soil layer, landscape database, ARA area, and ARA-LP cross-match files

Province	Total records[a]	Unique ARAs	Number of ARAs dropped[b]	Unique polygons	Total ARA - polygon combinations[c]	Number of polygon codes dropped[d]	Unique soil codes	Number of soil codes dropped[e]
Alberta	1,423	80	19	425	986	622	98	22
Manitoba	119	40	23	105	105	144	45	14
Saskatchewan	1,081	106	12	669	669	226	130	390

[a] There are more records than landscape polygons because double accounting is made for those polygons that have both dominant and subdominant soils. For Alberta, the number of records is even greater because of the reasons given in Table 1.

[b] The ARAs dropped that were originally in the ARA-LP cross-match files are predominantly nonagricultural and are not relevant for this study.

[c] Because landscape polygons can exist in more than one ARA in Alberta, there is a total of 986 ARA-polygon combinations in the final data set instead of 425. These 986 pologons are in fact unique, because of differing climate between ARAs.

[d] The landscape polygons dropped that were originally in the ARA-LP cross-match files were either located in an excluded ARA or posessed a dominant and/or subdominant soil codes that did not have matching layer data in the soil layer files. For Alberta, the dropped polygons represent the difference between the ARA-polygon combinations (1,608) in the cross-match file minus the 986 combinations in the final selected set.

[e] Soil codes dropped exist in the soil layer files but do not exist as a dominant or subdominant soil in any of the landscape polygons.

It is emphasized that the total number of polygons in Alberta should be described in terms of total ARA-landscape polygon combinations rather than by unique polygon codes, as shown in Table 16. As previously explained, this is due to the fact that landscape polygons cross ARA boundaries in Alberta. Each of these ARA-polygon combinations becomes a new, unique landscape polygon because of different climates between ARAs (even though the landform and other associated characteristics of each polygon do not change between ARAs). Henceforth, the number of landscape polygons for the final Alberta soil layer and landform database is set at 986.

A.1. Soil and vegetation characteristics of the landscape polygons

Table 17 summarizes the selected soils by landscape polygon and dominant and/or subdominant classification. Of the soils selected, 84, 91, and 78 percent are classified as dominant for at least one landscape polygon in Alberta, Manitoba, and Saskatchewan, respectively. Approximately the same number of soils are classified as subdominant at least once in Alberta and Saskatchewan as compared with the dominant soils, while less than half of the soils indicated as dominant in Manitoba are categorized as subdominant (note that many of the soils appear as both dominant and subdominant, depending on the landscape polygon). From the perspective of the landscape polygons, 89, 87, and 95 percent of the selected polygons contain a dominant soil for Alberta, Manitoba, and Saskatchewan, respectively. For Alberta and Saskatchewan, roughly two-thirds of the polygons also contain a subdominant soil, but only about 25 percent of the Manitoba polygons have a subdominant soil. As shown in Table 17,

Table 17. Summary of dominant and subdominant soil information for the soil database

Province	Total landscape polygons	Soil codes classified at least once as dominant[a]	Soil codes classified at least once as subdominant[a]	Landscape polygons with dominant soils	Landscape polygons with subdominant soils	Landscape polygons that contain both dominant and subdominant soils	Landscape polygons that contain only a dominant soil	Landscape polygons that contain only a subdominant soil[b]
Alberta	986	82	78	873	550	437	436	113
Manitoba	105	41	18	91	28	14	77	14
Saskatchewan	669	101	106	634	447	412	222	35

[a] The totals for these two columns indicate the total number of unique soil codes that appear in at least one landscape polygon as a dominant or a subdominant soil. Depending on the soil, it may exist as both a dominant and a subdominant soil, or only as a dominant or a subdominant soil, within a given province.

[b] All landscape polygons have a dominant soil type. However, in some cases only a subdominant soil emerges for a polygon in the final data set because the dominant soil does not exist in the soil layer data files.

further queries of the data produced information on the number of polygons that have both a dominant and subdominant soil, and the number of polygons that contain only a dominant or a subdominant soil.

From the perspective of EPIC, it makes no difference whether a soil is classified as dominant or subdominant. In either case, the types of soil layer inputs and landform inputs to the model are the same. The EPIC simulations that are being performed to construct the environmental metamodels include runs using both dominant and subdominant soils that were selected within an experimentally designed statistical sampling procedure (this will be described in detail in the forthcoming Report 3). The major distinction between the dominant and subdominant soils within a landscape polygon is that the dominant soil covers a greater percentage of land area as compared to the subdominant soil.

The vegetation characteristics of the selected landscape polygons are given in terms of dominant and subdominant soil types in Table 18. Polygons that are primarily agricultural have dominant vegetation types that are identified as being either agricultural crops (A) or parkland (P), which is a combination of cropland, grassland, and meadow intermixed with Aspen forest stands. Of the dominant soil-landscape polygon combinations selected for Alberta, Manitoba, and Saskatchewan, 63, 86, and 76 percent, respectively, are dominated by either the A or P vegetation types (column four of Table 17). Approximately 62, 68, and 79 percent, respectively, of the Alberta, Manitoba, and Saskatchewan subdominant soil - landscape polygon combinations are predominantly vegetation types A and P (column 5 of Table 17). Table 18 also shows that a significant number of the selected polygons are dominated by grassland (G), forest (C, D, and M) and other vegetation types that appear to contain little agricultural cropping.

Table 18. Summary of vegetation characteristics for the selected landscape polygons[a]

Province	Total landscape polygons	Polygons dominated by A vegetation		Polygons dominated by P vegetation		Polygons dominated by G vegetation		Polygons dominated by C, D, or M vegetation		Polygons dominated by other vegetation	
		D[b]	SD	D	SD	D	SD	D	SD	D	SD
Alberta	986	483	160	66	180	151	136	173	35	0	39[c]
Manitoba	105	73	18	5	1	1	1	12	8	0	0
Saskatchewan	669	433	322	46	31	86	53	69	39	0	2

[a] The vegetation codes indicate the dominant vegetation for each landscape polygon as follows: A-agricultural crops, P-parkland (cropland, grassland, and meadow intermixed with Aspen forest stands), G-grassland (perennial native grassland or improved pasture), D-deciduous forest (mainly broadleaf species), C-coniferous forest (mainly needle-leaved, cone-bearing species), and M-mixed deciduous and coniferous forest. See Shields et al. (1991) for a complete description of all vegetation codes.

[b] D and SD represent dominant and subdominant soil types, respectively.

[c] Of these 39 polygons in Alberta, 32 are described as "-" indicating that the major vegetation type is unknown.

A.2. Aggregation issues for the soil data

To perform the aggregation of the environmental metamodel results to the RS-CRAM region level, additional data describing the percent of each landscape polygon that is cultivated will be used. For Alberta and Manitoba, the percent of each polygon that has been cultivated have been received from Tajek (1993) and Shields (1993), respectively (these percentages are decile values, i.e., to the nearest 10 percent). The total cultivated acres for the two provinces are then computed by multiplying the total polygon area by these percentages. For Saskatchewan, the cultivated area for each landscape polygon has been received in the form of the total cultivated acres for each landscape polygon from Padbury (1993). Using these cultivated areas avoid the problem of trying to determine how much of each polygon is cultivated based on the vegetation codes described above.

However, an additional issue that still must be addressed is that many of the selected ARAs have only a subset of the original landscape polygons that exist in the ARA-LP cross-match files. While it is likely that the dropped polygons are agriculturally insignificant, it is possible that important agricultural areas have been dropped. This could have important implications for the weighting of the environmental indicators by soil acreage. For example, it is possible that too much weight could be placed on a given landscape polygon-ARA combination during the aggregation to the CRAM region if other polygons within the ARA that contain important agricultural area have been dropped. A review of the dropped ARAs and landscape polygons will be performed in consultation with Agriculture Canada personnel to identify if any problems of this nature might occur.

A.3. Slope and slope lengths

As previously noted, the land surface slope and slope length values are key input variables for estimating water erosion in EPIC. These variables are used in EPIC to estimate the USLE LS factor with the following equation developed by Wischmeier and Smith (1978):

$$LS = \left[\frac{\lambda}{22.1}\right]^{M}(65.41S^{2} + 4.56S + 0.065) \tag{13}$$

where λ is the slope length (m), S is the land surface slope (m/m), and M is parameter, calculated:

$$M = \frac{0.35}{\left[S + e^{(-1.47-61.09S)}\right] + 0.2} \tag{14}$$

Previously estimated slope lengths for Alberta, Manitoba, and Saskatchewan (Tables 19, 20, and 21) have been incorporated for each soil on the basis of the dominate surface landforms for the dominant and subdominant landscapes in each landscape polygon. These slope length estimates are further classified by slope class for Alberta and Saskatchewan. For Manitoba, it is assumed that a slope length is the same across all slope classes for a given landform.

Midpoint values of the six slope categories (A, B, C, D, E, and F) given in the Landscape Database are used. Most of the slopes in the Landscape Database fall within the A (1-3 %), B (4-9 %), and C (10-15 %) gradient categories; a few of the slopes are classified as D (16-30 %). The midpoint values of these ranges (2 % for A, 6.5 % for B, 12.5 % for C, and 23 % for D) are assumed to represent the land surface slopes for each soil that falls within one of the four classes.

Table 19. Alberta slope lengths by local surface forms and slope class[a]

Local surface form (landform)	Slope class[b]	Estimated slope length (m)
Dissected		
	B	70
	C	55
	D	40
	E	25
Hummocky	B	50
	C	30
	D	30
Knollkettle		60
	B	70
	C	35
	D	30
Level	A	300
Rolling		
	B	100
	C	90
	D	90
Ridged	A	20
	B	30
	C	45
Undulating	A	60
	B	60

[a] From Tajek (1993)

[b] Slope ranges for the different classes are as follows: A - 1-3%, B - 4-9%, C - 10-15%, D - 16-30%, E - 31-60%

Table 20. Manitoba slope lengths by local surface form[a]

Local surface form (landform)	Estimated slope length (m)
Dissected	62
Hummocky	154
Inclined	185
Knoll/kettle	92
Level	308
Rolling	185
Ridged	92
Steep	92
Undulating	185
Veneer	154

[a] From Eilers et al. (1987).

Table 21. Saskatchewan slope lengths by local surface form and slope class[a]

Local surface form (landform)	Slope class[b]	Estimated Slope length
Dissected	A B C D	90 110 130 150
Hummocky	A B C D	40 50 60 70
Knoll/Kettle	A B C D	40 50 60 70
Level	A	100
Rolling	B C D	80 97 110
Ridged	A B C D	40 50 60 70
Undulating	A B	80 97

[a] From Padbury (1993).

[b] Slope ranges for the different classes are as follows: A - 1-3%, B - 4-9%, C - 10-15%, D - 16-30%

A.4. Determination of hydrologic groups

A key soil-related input to EPIC is the hydrologic group, which is used in the previously described runoff curve number calculations to determine the amount of surface runoff that occurs for a daily rainfall event. By definition, a hydrologic soil group (A, B, C, or D) is a group of soils that possess the same runoff potential for similar storm and vegetation cover conditions (see definitions in Table 22). The runoff potential is based on the minimum infiltration rate that is measured for a bare soil after prolonged wetting under unfrozen conditions. The soil properties that affect the minimum infiltration rate include the depth to a seasonably high water table, intake rate and permeability after prolonged wetting, and depth to a layer that impedes water flow. The determination of a hydrologic group for a soil is a subjective process that usually involves expert opinion.

Soil properties and other information provided in the layer data and Landscape Database that can potentially be used to determine the hydrologic group for each of the selected soils in the final data set include texture (percent sand, silt, and clay), hydraulic conductivity, drainage class, type of compacted layer, and depth to the compacted layer. It was decided that hydraulic conductivity values should not be considered because their reliability is somewhat questionable. Therefore, estimates of the hydrologic groups were made using textural classification.

The initial textural designations used to group the soils into the four hydrologic groups were developed in consultation with Bauer (1993) and are overlain on the standard textural

Table 22. Definitions of the four hydrologic groups[a]

Hydrologic group	Definition
Group A (low runoff potential)	Soils having high infiltration rates even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission.
Group B	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
Group C	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
Group D (High runoff potential)	Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay-pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

[a] From Bauer (1993).

triangle in Figure 8. The assumptions based on texture are: (1) soils with more than 70 percent sand but less than 20 percent clay are in group A, (2) soils that have less than 30 percent clay and do not lie within the group A textural range are in group B, (3) soils with more than 30 percent clay but less than 40 percent clay are in group C, and (4) soils with greater than 40 percent clay are in group D.

These designations were submitted to experts in Alberta, Manitoba, and Saskatchewan for their review, and for any necessary revisions. The hydrologic group designations for Manitoba were reviewed by Fraser (1993); no changes were considered necessary to the initial classifications made based on the textural classifications. However, the hydrologic group classifications for Alberta and Saskatchewan were modified based on the rules developed by Tajek (1993) as shown in Table 23.

A.5. EPIC soil layer inputs

The standard set of EPIC soil layer input variables is listed in Table 24. The minimum required data set includes layer depth (Z), bulk density (BD), sand content (SAN), silt content (SIL), soil pH (PH), and organic carbon (CBN). These variables, as well as the sum of bases (SMB), calcium carbonate (CAC), cation exchange capacity (CEC), and coarse fragment content (ROK) are contained in the soil layer data provided for Alberta, Manitoba, and Saskatchewan. Values for wilting point (U), field capacity (FC), and saturated hydraulic conductivity (SC) also exist in the soil layer data files. However, because these three variables are estimated with procedures that are different than those used in EPIC, it is recommended by Izaurralde et al. (1992) to let the model calculate U, FC, and SC internally as a function of other soil inputs.

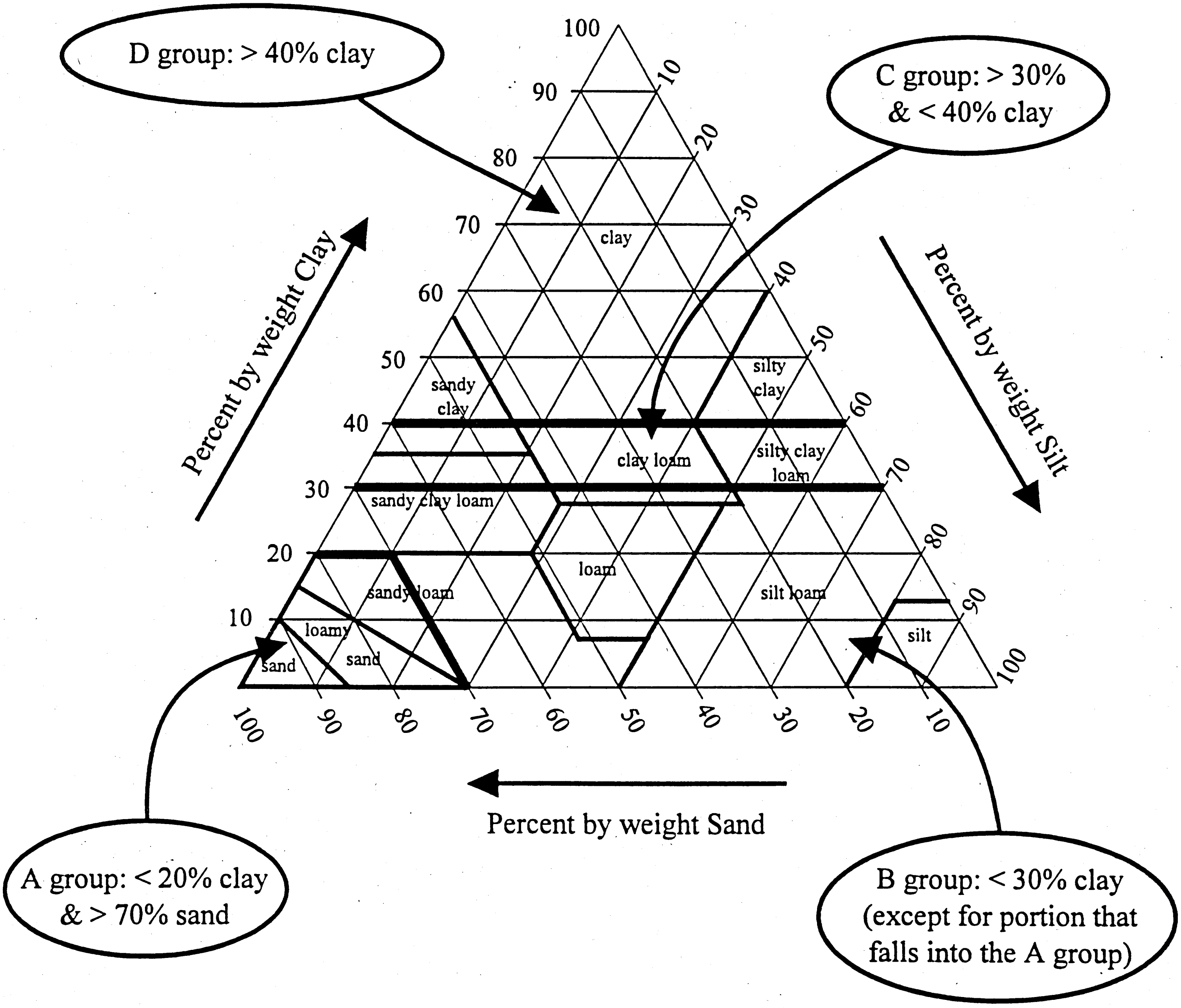

Figure 8. Assumed textural classifications for hydrologic groups A, B, C, and D overlaid on the textural triangle (textural triangle taken from Hillel 1982)

Table 23. Rules for use of hydrologic soil group with EPIC in Alberta and Saskatchewan[a]

Hydrologic group	Texture group	Texture	Sand (%)	Clay (%)	Other conditions
A	1	sand, loamy sand, sandy loam	>= 65	-	Include soils with > 70% course fragments
B	2	silt, silt loam, loam, sandy clay	< 65	<= 30	Exclude soils with B_t < 40 cm from surface
C	3	silty clay, clay, sandy clay	-	> 30 and < 60	Includes soils from texture group 2 that have either water table < 75 cm or B_t^b < 40 cm or soils with B_{nt}^b < 30 cm from surface
D	4	heavy clay	-	>= 60	Includes soils with B_{nt}^b < 30 cm, water table < 50 cm, and lithic soils with rock < 50 cm from surface

[a] From Tajek (1993).

[b] The B_t horizon is a clay enriched B horizon that occurs in luvisolic soils; the Bnt horizon is a clay and sodium enriched horizon that occurs in solonetzic soils. These horizons tend to swell greatly when wet, resulting in higher runoff.

Table 24. EPIC soil layer data inputs[a]

Variable	Definition	Units	Available from layer data?
Z[b]	Depth from the surface to the bottom of the soil layer	m	yes
BD[b]	Bulk density of the soil layer (33 kPa)	t m^{-3}	yes
U	Wilting point (1500 kPa for many soils)	m m^{-1}	no[c]
FC	Field capacity (33 kPa for many soils)	m m^{-1}	no[c]
SAN[b]	Sand content	%	yes
SIL[b]	Silt content	%	yes
WN	Organic N concentration	gt^{-1}	no
PH[b]	Soil pH	---	yes
SMB[b]	Sum of bases	cmol kg^{-1}	yes
CBN	Organic carbon	%	yes
CAC	Calcium carbonate	%	yes
CEC	Cation exchange capacity	cmol kg^{-1}	yes
ROK	Coarse fragment content	%	yes
WNO3	Nitrate concentration	gt^{-1}	no
AP	Labile P concentration	gt^{-1}	no
RSD	Crop residue	t ha^{-1}	no
BDD	Bulk density (oven dry)	t m^{-3}	no
PSP	Phosphorus sorption ratio	---	no
SC	Saturated conductivity	mmh^{-1}	no[c]
RT	Subsurface flow travel time	d	no
WP	Organic P concentration	gt^{-1}	no

[a] From Williams et al. (1990b).

[b] Z, BD, SAN, SIL, PH, and CBN are the minimum required input set. Default values of zero can be entered for the other variables, which are either then ignored or calculated internally in EPIC.

[c] Wilting point, field capacity, and saturated hydraulic conductivity values do exist in the Alberta, Manitoba, and Saskatchewan soil layer data files. However, because these values are obtained by different procedures than those used in EPIC, it is recommended by Izaurralde et al. (1992) that they not be used in the model. Therefore, they will be calculated internally in EPIC based on other soil layer data inputs.

Default values of zero are entered for these and the other variables for which data are not available. An example set of input data for soil ABC from Alberta is given in Table 25.

A minimum of three and maximum of 10 soil layers are input into EPIC. In a few cases, soil data provided for Saskatchewan that contained only one or two layers had to be split so that the minimum input requirement of three layers is met. However, this does not change the properties of these soils and will have little impact on the output of the model. All of the soil data provided for Saskatchewan has a maximum depth of 1.0 m. The maximum depths of the Alberta and Manitoba data varied between 1.0 and 2.0 m. Transformation of all the soil layer data provided for the Prairie Provinces has been performed, even though only part of each data set will be used in the analysis as shown in Table 16.

B. Development of the Weather Database

Figure 9 depicts the steps required to process the available weather data into EPIC weather generator tables and wind arrays. Although the historical ARA database 31-year weather records have daily values of precipitation, and maximum and minimum temperature, the weather generator tables are still required to generate daily values of windspeed, solar radiation, and relative humidity (and for other internal stochastic processes). Alternatively, they can be used to generate complete weather records for as many years of simulation as desired. Weather generator tables have been developed for each ARA; an example of a weather generator table for ARA 4 in Saskatchewan is shown in Table 26. The ARA database weather records have also been processed into an EPIC format.

Table 25. Example of EPIC soil array for soil ABC in Alberta[a]

	Layer[b]					
EPIC variable[c]	1	2	3	4	5	6
Z[d]	0.01	0.18	0.23	0.58	0.91	1.00
BD	1.30	1.30	1.30	1.50	1.50	1.50
U	0.00	0.00	0.00	0.00	0.00	0.00
FC	0.00	0.00	0.00	0.00	0.00	0.00
SAN	45.00	45.00	43.00	41.00	42.00	43.00
SIL	30.00	30.00	29.00	27.00	28.00	29.00
WN	0.00	0.00	0.00	0.00	0.00	0.00
PH	5.20	5.20	4.60	4.30	4.90	5.50
SMB	16.80	16.80	9.60	14.40	14.90	15.60
CBN	2.00	2.00	0.40	0.40	0.40	0.50
CAC	0.00	0.00	0.00	0.00	0.00	0.00
CEC	24.00	24.00	13.00	15.00	18.00	17.00
ROK	5.00	5.00	5.00	5.00	5.00	5.00
WNOS	0.00	0.00	0.00	0.00	0.00	0.00
AP	0.00	0.00	0.00	0.00	0.00	0.00
RSD	0.00	0.00	0.00	0.00	0.00	0.00
BDD	0.00	0.00	0.00	0.00	0.00	0.00
PSP	0.00	0.00	0.00	0.00	0.00	0.00
SL	0.00	0.00	0.00	0.00	0.00	0.00
RT	0.00	0.00	0.00	0.00	0.00	0.00
WP	0.00	0.00	0.00	0.00	0.00	0.00

[a] Soils are identified as three letter codes in the soil layer data received for Alberta, Manitoba, and Saskatchewan.

[b] Every soil is automatically split into 10 layers in EPIC, irregardless of the number of layers entered.

[c] See Table 19 for description of EPIC soil layer variables.

[d] Z represents the depth in m from the soil surface to the bottom of the respective layer.

Table 26. Example of EPIC weather generator table with monthly weather statistics for ARA 4 in Saskatchewan

EPIC variable[a]	Month												Units
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
OBMX	-11.3	-7.3	-.6	10.2	18.3	23.2	27.1	26.2	18.9	12.2	.3	-7.6	•C
OBMN	-21.7	-18.2	-11.3	-2.3	4.1	9.1	11.9	10.5	4.6	-1.1	-9.9	-17.8	•C
SDTMAX	8.9	8.1	7.7	7.4	6.5	4.8	4.3	5.4	6.9	7.1	8.1	8.3	•C
STDMIN	8.5	8.5	8.1	4.7	4.4	3.6	3.2	3.5	4.2	4.4	6.9	8.1	•C
SMY	17.1	15.4	16.9	31.0	48.1	64.6	51.8	52.3	40.8	22.6	15.6	18.4	mm
RST(2)	1.98	2.34	2.41	4.88	4.97	6.10	5.90	6.62	6.91	4.67	2.47	2.69	mm
RST(3)	2.271	2.595	2.099	2.530	2.543	3.130	2.887	3.855	2.820	3.089	1.989	2.670	-
PRW1	.224	.222	.184	.194	.259	.370	.320	.279	.197	.146	.174	.195	-
PRW2	.476	.431	.446	.511	.580	.579	.511	.532	.520	.471	.434	.459	-
WVL	9.3	7.9	7.7	8.5	11.8	14.0	12.3	11.6	8.7	6.7	7.1	8.2	d
WZ	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	mm
OBSL	5.14	8.85	13.93	17.77	21.19	22.92	23.60	19.57	13.85	8.72	4.88	3.81	MJ m^{-2}
RH	76.0	76.0	75.0	63.0	59.0	60.0	59.0	58.0	62.0	62.0	73.0	77.0	%

[a] See Table 4 for a description of each weather variable.

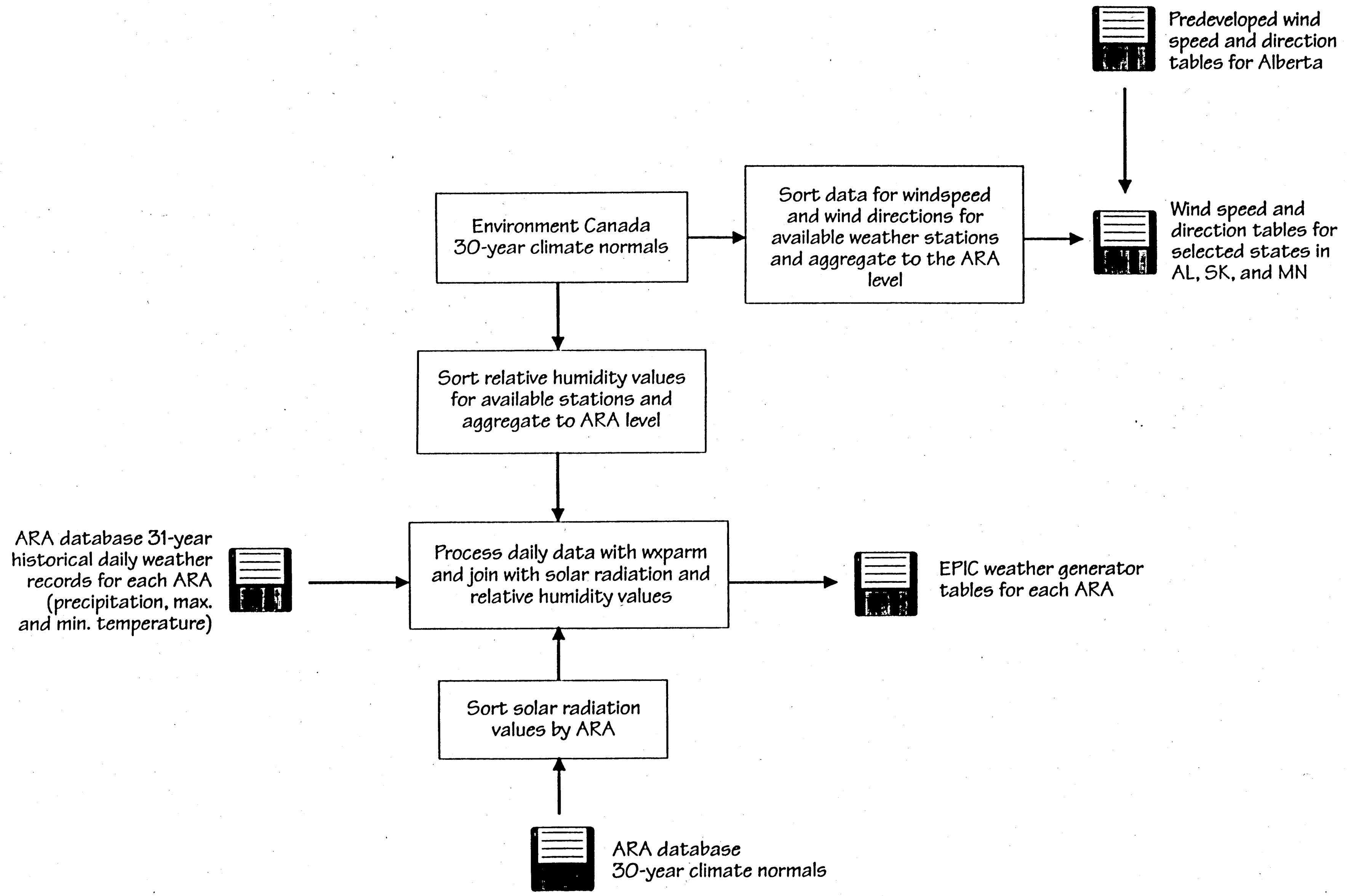

Figure 9. Development of EPIC weather generator tables and wind arrays (for the wind erosion submodel) for Alberta, Saskatchewan, and Manitoba

The major step involved in processing the weather data was the manipulation of the ARA database daily values in WXPARM, a program provided with the EPIC model upon request. This step provided automatic calculation of all the precipitation and temperature values required for the weather tables. Solar radiation values available for each ARA from the ARA database climate normals were inserted into the tables after the precipitation and temperature data were analyzed. These solar radiation values are derived from a limited number of climate stations that collect solar radiation data.

Additional steps are required to process the relative humidity data, which are available for limited stations in the Prairie Provinces from 30-year Environment Canada climate normals as shown in Figure 10. First, an average value was calculated for the monthly relative humidity because two values (6:00 a.m. and 3:00 p.m.) are given for each station. Then, the relative humidity values are aggregated across ARAs so that each ARA monthly weather table has a set of relative humidity values. This step was accomplished using the Thiessen polygon weighting technique in a manner similar to that performed by De Jong et al. (1992) for a network of weather stations within ARAs.

The wind arrays consist of monthly average wind speeds and 16 monthly wind direction components that are required as inputs to the EPIC wind erosion submodel. The wind data are available for only limited stations in the Prairie Provinces (Figure 11), in many cases the same stations as those that have relative humidity and solar radiation data. Thus, the wind date is also aggregated to the ARA level using the Thiessen polygon weighting technique. A predeveloped set of complete wind arrays are already available for 24 climate stations in Alberta. Wind arrays for Saskatchewan and Manitoba have been constructed from Environment Canada 30-year

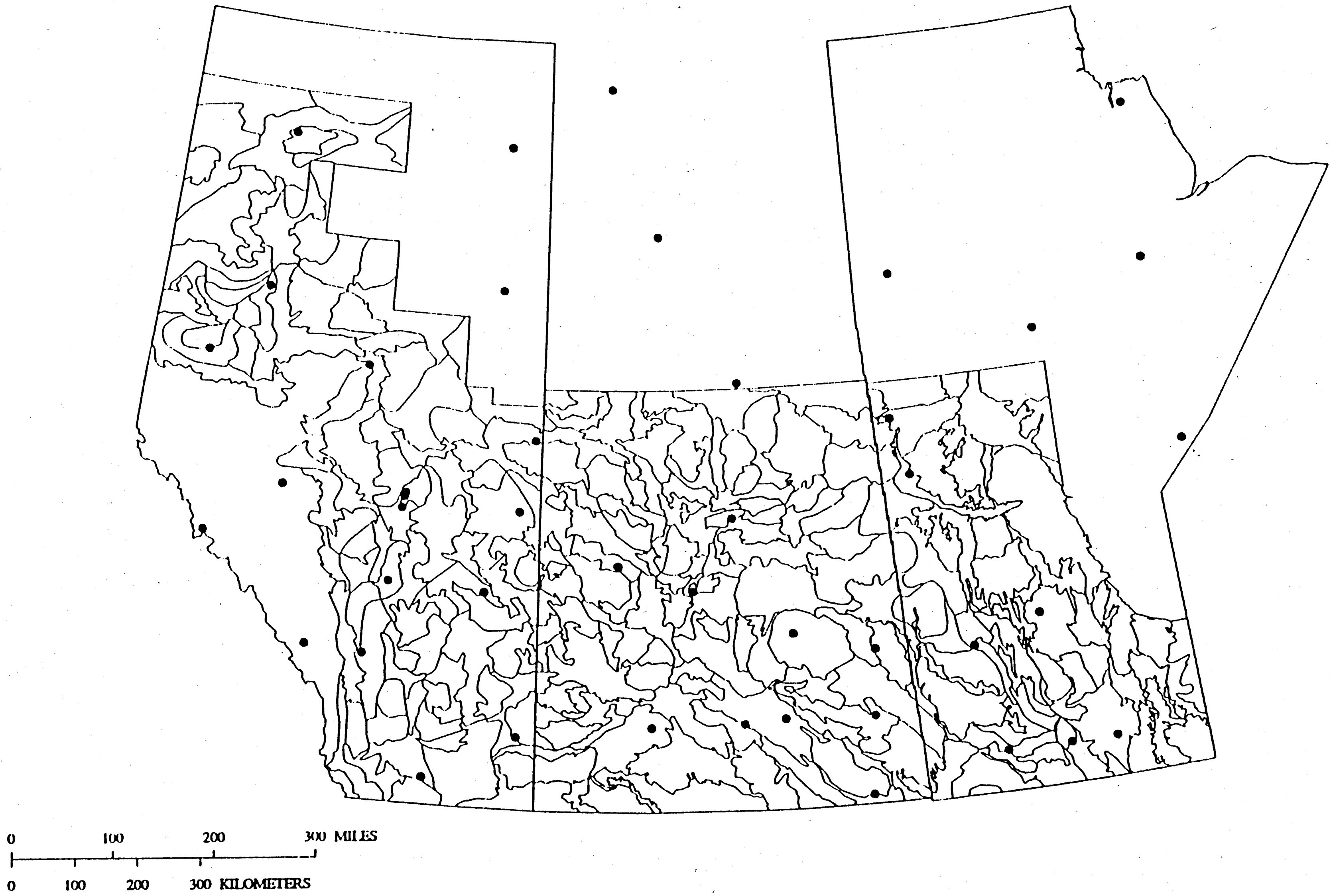

Figure 10. Locations of climate stations (●) in the Prairie Provinces that possess relative humidity data (ARA boundaries are shown for each province)

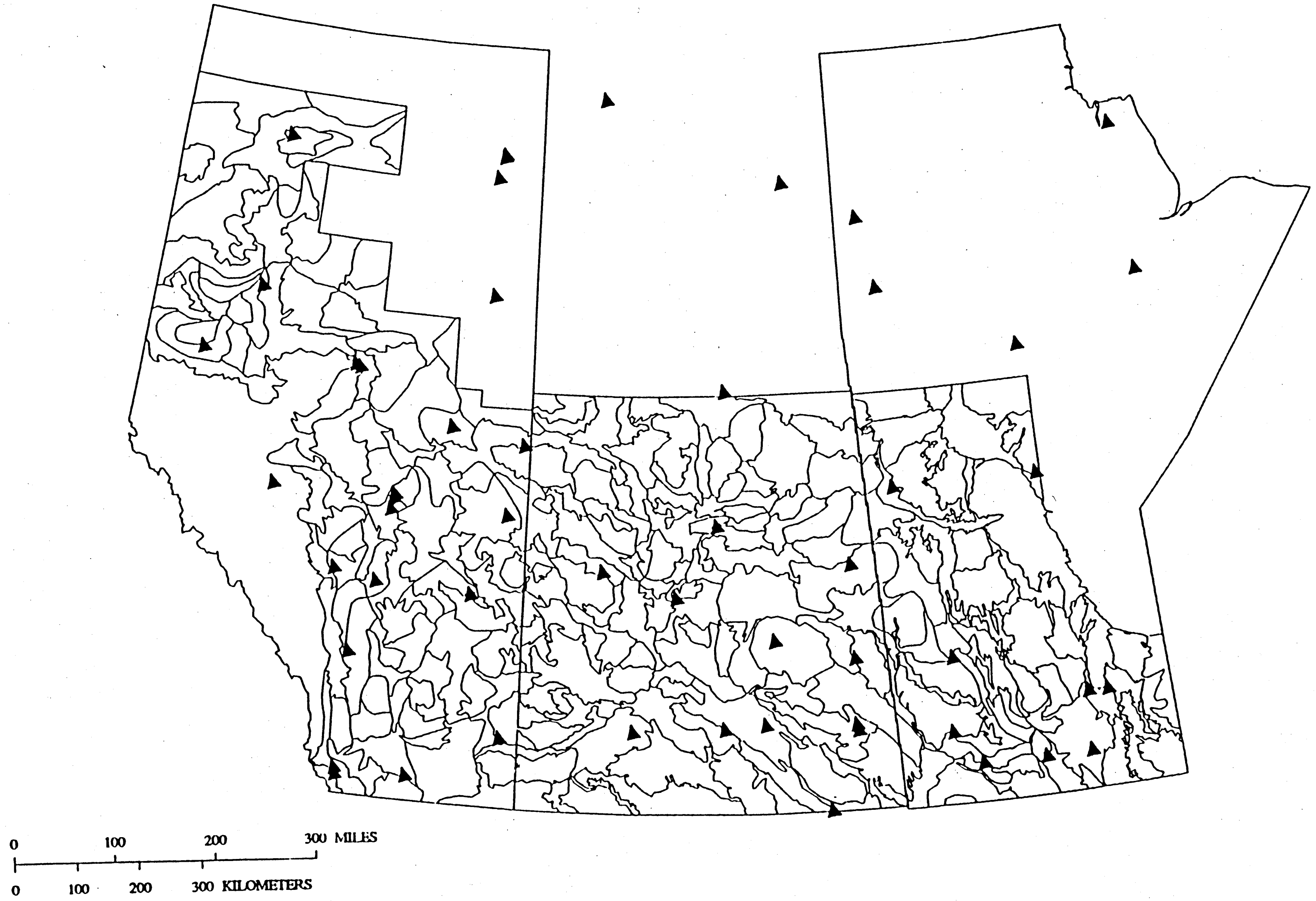

Figure 11. Locations of climate stations (▲) in the Prairie Provinces that possess sufficient data to construct EPIC wind arrays (ARA boundaries are shown for each province)

climate normals. An example of a wind array for the Edmonton, Alberta Municipal Airport is shown in Table 27.

IV. CALIBRATION AND TESTING OF EPIC FOR THE PRAIRIE PROVINCES

EPIC has been undergoing continuous development in the United States since its inception in the early 1980s. Although the model has proven to be flexible for a variety of conditions, additional testing is required for conditions in Western Canada. Thus, calibration and test runs are being performed prior to the EPIC simulations that will be used to construct the metamodels (Figure 2). The primary objectives of the calibration process are: (1) to develop and/or modify the EPIC crop parameters required for the analysis, (2) to test the EPIC crop growth model against measured yields, and (3) to assess the model's accuracy in predicting wind and water erosion, the key environmental indicators for the project. It is emphasized that no modifications are being made to the structure or code of EPIC in adapting the model to the Prairie Provinces. The only changes that are being made are to standard inputs that have been developed for conditions in the United States.

Testing of the crop parameters for several crops has been performed by comparing EPIC predicted yields with measured yields (see section III.C.). Calibration of the wind and water erosion submodels, as well as other environmental indicators, is a more difficult task due to the lack of complete data sets. Most of the sites where erosion losses have been measured in the Prairie provinces lack sufficient data to truly test EPIC. Thus, the calibration process is limited to more generalized comparisons with observed erosion rates. This is further discussed in section IV.C.1. The testing described for Alberta in section IV.A. was performed with

Table 27. Example of monthly wind array for the Edmonton, Alberta Municipal Airport

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average wind speed (m/s)	3.61	3.61	3.83	4.31	4.47	4.28	3.89	3.72	4.06	3.97	3.75	3.61
Direction	Time (%)											
N	6.30	6.10	8.40	7.10	7.30	8.50	8.20	6.00	8.10	3.90	8.20	4.80
NNE	3.60	3.30	3.80	4.40	4.20	3.70	3.10	3.80	3.10	1.60	2.00	2.60
NE	4.50	4.80	5.30	4.70	5.00	4.50	3.30	3.70	3.20	2.40	3.40	3.80
ENE	3.40	4.70	4.40	4.00	4.20	3.90	3.50	3.20	3.00	2.00	2.90	3.00
E	3.50	4.40	4.50	4.20	5.00	4.50	4.30	4.00	3.30	2.50	3.50	3.90
ESE	2.40	3.50	3.90	4.50	4.90	4.50	3.50	3.30	3.30	2.50	2.60	2.80
SE	3.80	4.00	5.50	6.20	8.50	5.30	4.30	4.20	4.40	4.10	3.70	3.60
SSE	4.20	5.90	7.10	8.50	8.30	5.90	5.60	5.50	5.60	6.20	5.60	5.10
S	12.40	14.40	14.70	13.80	10.20	7.60	8.20	10.40	11.00	15.90	15.50	13.30
SSW	9.70	9.00	6.80	5.90	4.30	4.90	5.50	6.10	7.10	9.60	10.30	11.20
SW	6.60	7.70	4.60	3.90	3.30	3.90	5.10	5.50	5.50	8.10	7.90	8.00
WSW	4.40	4.50	3.60	2.80	3.00	4.40	5.00	4.60	4.10	5.20	5.20	5.00
W	7.60	6.60	5.30	5.00	6.20	9.40	10.50	9.60	8.60	9.20	8.00	7.30
WNW	8.80	6.30	6.80	6.90	8.20	10.90	11.20	10.30	10.30	9.40	8.70	7.40
NW	7.60	5.30	6.70	6.80	8.50	9.40	9.30	9.10	9.50	8.20	6.70	6.60
NNW	6.00	5.00	6.00	7.20	7.20	6.70	6.40	5.90	7.10	4.80	4.60	5.80

EPIC 1910 while the tests the of crop parameters discussed in section IV.B. was performed with EPIC 0941. The remaining tests described in sections IV.B.1, IV.B.2, and IV.C. were performed with EPIC 3090 unless otherwise stated.

A. EPIC Testing in Alberta

Extensive testing of EPIC in Alberta has already been performed by Izaurralde et al. (1992) and it is applicable to this project. These simulations included both direct comparisons with research plot data, as well as runs representative of larger fields and entire ARAs. At the research plot scale, simulated yields were compared with measured yields for: (1) two "simulated erosion" (obtained by scraping away topsoil) sites in Strathcona County, Alberta (Solberg et al. 1992); (2) for a 12-year (1980-91) spring wheat-fallow rotation at Lethbridge; and (3) for two years of irrigated spring wheat (1985-86) that were also grown at Lethbridge. Generalized simulations were performed for two field-scale sites at Del Bonita and St. Paul and for two ARAs, N2 (Edmonton) and N5 (Cooking Lake).

Figure 12 shows how the yields predicted by EPIC compared with measured yields on a Black Chernozemic soil for five different levels of simulated erosion and three levels of fertilizer inputs. EPIC captured the trend of decreasing productivity with increased erosion but tended to underpredict yields for the fertilized treatments. Overall, observed and simulated yields were significantly correlated, yielding an R-square of 0.67 for the 30 combinations of soil type, fertilizer treatments, and erosion levels. It was concluded that EPIC can simulate erosion, soil properties, and amendment effects on soil productivity for these Alberta conditions.

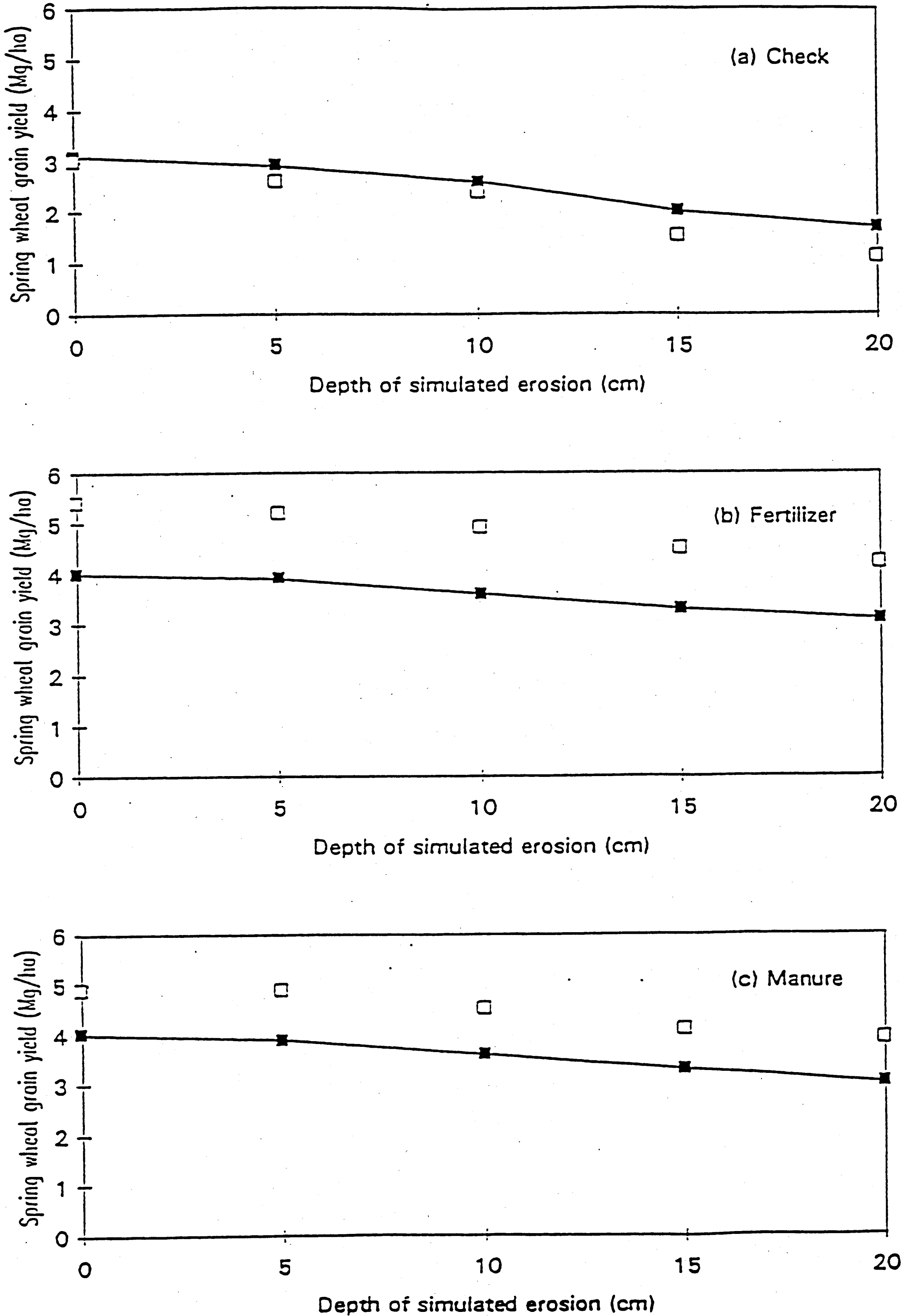

Figure 12. Predicted (■) versus observed (□) 1991 spring wheat yields for five levels of simulated erosion and three levels of fertilizer inputs (check - no fertilizer; fertilizer - N at 100 kg/ha and P at 20 kg/ha; manure - 75 mg/ha on a dry basis) on a Chernozemic soil located in Shrathcona County, Alberta (from Izaurralde et al. 1992)

For the 12-year wheat-fallow rotation it was found that EPIC did not accurately track the year to year variability in yields. Predicted water erosion losses for the 12-year wheat-fallow rotation were very low relative to the estimated wind erosion losses, which is consistent with expectations for the site (no measured erosion data were available). Also, predicted wind erosion losses were 2.5 times higher under a cultivated fallow system (conservation tillage) than under a chemical fallow system (herbicide with no tillage). This result is again consistent with expectations and indicates the model's ability to differentiate between management practices. The 1985-86 irrigated spring wheat yields at Lethbridge were more realistically simulated by EPIC, which correctly identified that yields were higher in 1985 as opposed to 1986 over several different fertilizer treatments.

A key objective of the field-and ARA-scale simulations was to assess EPIC's ability to estimate erosion, with resulting effects on soil and landscape productivity in Alberta. Erosion losses estimated by EPIC for the field sites and ARAs generally fell within the bounds of measured erosion for the region. However, a lack of detailed field data precluded any true validation of simulated and measured values.

Izaurralde et al. (1992) concluded that overall EPIC produced reasonable crop yield estimates for several Alberta scenarios including irrigated and dryland conditions, continuous and fallow cropping sequences, different soil types, simulated erosion levels, and different fertilizer rates. It was recommended that ARAs be adopted as the basis to assess the economic impact of erosion in Alberta. However, it was emphasized that EPIC should be used for relative comparisons of different scenarios as opposed to relying on it to provide absolute values, especially at the ARA level.

B. Testing of EPIC Crop Growth Model

A complete set of crop parameters (Table 28) has been developed for the 10 crops that will be simulated in the analyses of GRIP and NISA (alfalfa and bromegrass will both be used to represent tame hay). Calibration and testing of the EPIC crop parameters has focused primarily on spring wheat, barley, fall rye, grasses, and canola. Predeveloped parameters will be relied upon for the other crops.

Comparisons of measured and simulated yields are presented in Table 29 for spring wheat, barley, fall rye, and different grasses. In general, the simulated yields compared favorably with those reported from the experimental data. The major exception to this trend was the low mean yield reported for russian wildrye at Mandan, North Dakota. Simulation of wild rye yields by EPIC is more accurate once the crop is established, which is the third year after seeding. This is reflected in the yield comparisons with the measured data reported by White and Wight (1981). However, specific yields for each cropping year were not reported for the Mandan, North Dakota data. Additional test results for canola are presented in Table 30 for selected sites in Alberta and Manitoba. Again, the simulated yields compare reasonably well with those measured.

B.1. Testing for southwest Manitoba simulated erosion sites

Further testing of the calibrated parameters for canola and spring wheat have been performed for two of six simulated erosion sites in southwest Manitoba reported by Smith and Shaykewich (1990). Simulated erosion was performed at these sites by scraping the topsoil away for depths of 5, 10, and 20 cm. Predicted crop yields are compared only for the noneroded soil and the simulated 20 cm eroded soil. Input data for the simulations were obtained primarily

Table 28. Crop parameters selected for the EPIC simulations[a]

	Crop									
Variable	Spring Wheat	Barley	Fall Rye[b]	Canola	Sunflower	Alfalfa[c]	Bromegrass[c]	Flax	Lentils	Field Pea
WA	35.0	35.0	30.0	34.0	60.0	20.0	35.0	25.0	25.0	25.0
HI	0.49	0.54	0.42	0.3	0.25	0.25	0.025	0.54	0.61	0.95
TB	25.0	25.0	15.0	21.0	25.0	20.0	25.0	22.5	22.5	15.0
TG	0.0	0.0	0.0	5.0	6.0	4.0	8.0	5.0	5.0	1.0
DMLA	3.0	3.0	3.0	4.5	5.0	5.0	5.0	2.5	5.0	5.0
DLAI	0.60	0.60	0.80	0.55	0.55	0.9	0.85	0.9	0.9	0.75
DLAP1	15.01	15.01	30.01	15.02	15.01	15.01	15.01	15.02	15.02	15.01
DLAP2	45.95	45.95	50.95	45.95	50.95	50.95	50.95	50.95	50.95	50.95
RLAD	1.0	1.0	1.0	0.3	1.0	2.0	2.0	1.0	1.0	2.0
RBMD	1.0	1.0	1.0	0.3	2.0	10.0	1.0	0.5	0.5	2.0
ALT	2.0	2.0	2.0	3.0	3.0	3.0	4.0	3.0	3.0	2.0
CAF	0.85	0.85	0.75	0.82	0.86	0.85	0.75	0.9	0.9	0.05
HMX	1.2	1.2	1.1	1.3	2.5	1.25	0.8	0.55	0.4	1.2
RDMX	2.0	2.0	2.0	0.9	2.0	2.0	2.0	2.0	2.0	2.0
CVM	0.03	0.01	0.03	0.1	0.2	0.01	0.003	0.2	0.2	0.01
CNY	0.025	0.021	0.023	0.038	0.028	0.025	0.0234	0.04	0.45	0.37
CPY	0.0022	0.0017	0.0037	0.0079	0.061	0.0035	0.0033	0.0033	0.0045	0.021
WSYF	0.45	0.49	0.05	0.18	0.01	0.01	0.01	0.01	0.01	0.1
PST	0.60	0.60	0.60	0.95	0.60	0.60	0.60	0.9	0.95	0.6
WCY	0.12	0.12	0.11	0.12	0.0	0.1	0.1	0.12	0.11	0.4
IDC	5	5	6	5	4	3	6	2	1	2
FIRST1	5.001	5.001	5.001	5.0	5.15	5.01	5.01	5.05	5.05	5.01
FRST2	15.01	15.01	15.01	15.01	15.95	15.95	15.95	15.10	15.10	15.1

Table 28 (Continued)

	Crop									
Variable	Spring wheat	Barley	Fall Rye[b]	Canola	Sunflower	Alfalfa[c]	Bromegrass[c]	Flax	Lentils	Field Pea
BN_1	0.0663	0.059	0.0226	0.044	0.05	0.0417	0.04	0.0482	0.044	0.0515
BN_2	0.0255	0.0226	0.018	0.0164	0.023	0.0290	0.029	0.0294	0.0164	0.0335
BN_3	0.0148	0.0131	0.0140	0.0128	0.0146	0.02	0.016	0.0263	0.0128	0.0296
BP_1	0.0053	0.0057	0.004	0.0074	0.0063	0.0035	0.028	0.0049	0.0074	0.0033
BP_2	0.002	0.0022	0.003	0.0037	0.0029	0.0028	0.0017	0.0024	0.0037	0.0019
BP_3	0.0012	0.0013	0.0034	0.0023	0.0023	0.002	0.0011	0.0023	0.0023	0.0014
BW_1	3.39	3.39	3.39	1.27	3.39	3.39	3.39	1.27	1.27	3.39
BW_2	3.39	3.39	3.39	0.6	3.39	3.39	3.39	0.63	0.63	3.39
BW_3	1.61	1.61	1.61	0.73	1.61	3.0	3.39	0.73	0.73	3.39

[a] See Table 6 for definitions of each variable (values of SDW, COSD, and PRY are not of importance and are not given here).

[b] Values are for altai wild rye.

[c] Alfalfa and bromegrass are assumed representative of tame hay.

Table 29. Measured and simulated (EPIC) yields for selected sites in Montana, North Dakota, Alberta, and Saskatchewan

Location/description	Crops	Measured yields (t/ha)	Simulated yields (t/ha)
Sydney, Montana; 1976 measured yields as given by White and Wight (1981)[a]	Crested wheatgrass Meadow bromegrass Altai wildrye Russian wildrye	4.4 3.0 4.2 4.4	4.4 2.6 3.8 4.1
Mandan, North Dakota; 7-year mean yields (Smika, Haas, and Rogler[b]) were compared against 10-year simulated yields using generated weather[c]	Crested bromegrass Bromegrass Russian wildrye	2.8 2.16 1.62	2.6 2.2 4.0
Lethbridge, Alberta; 1976 and 1977 measured yields for dryland wheat and barley (Major and Hamman 1991).[d] Mean yields for three years of corn (Major et al. 1991) compared with a 10-year simulated average yield using generated weather.	Wheat (1976) Wheat (1977) Wheat (mean) Barley (1976) Barley (1977) Barley (mean) Corn	3.1 2.6 2.85 3.3 3.8 3.55 11.9	3.69 2.85 3.27 3.93 3.39 3.66 9.9
Swift Current, Saskatchewan; measured mean yields for 12-year fallow-wheat and continuous wheat rotations (Campbell et al. 1983) were compared against simulated mean yields.[e]	Fallow-wheat rotation Cont. wheat rotation	1.39 1.7	1.39 1.82

[a] Crops were seeded in 1974, measured yields were obtained in 1975 and 1976. EPIC output was compared only for 1976 because 1975 was the first year after seeding and thus seasonal growth among species can be best compared from the 1976 yield curves.

[b] Reference date currently unavailable.

[c] EPIC best simulates wildrye forage production after establishment, the third year after seeding (as noted for the Sydney, Montana data). Measured yields for wildrye yields after such a period of establishment were not reported.

[d] Reported monthly rain totals (Major and Hamman 1981) for May, June, and July were used with the generated weather.

[e] Used Lethbridge, Alberta weather; actual monthly Swift Current rainfall totals were input for May, June, and July.

Table 30. Measured and EPIC (simulated) canola yields for selected sites in Alberta and Manitoba

Location/description	Years	Measured yields (t/ha)	Simulated yields (t/ha)
Winnipeg, Manitoba (Van Deynze et al. 1992)[a]	Mean[b]	1.35	1.82
Winnipeg, Manitoba (Morrison et al. 1990)[b]	1985	2.68	1.69
	1986	2.2/2.8[c]	2.68
	Mean	2.56	2.19
Lethbridge, Alberta[d] (Krogman and Hobbs 1975)	1971 dryland	0.81	0.72
	1972 dryland	1.68	1.66
	1973 dryland	1.0	0.63
	1971 irrigated	2.88	2.93
	1972 irrigated	3.2	2.9
	1973 irrigated	2.8	3.5

[a] The normal maximum potential LAI (DMLA) value of 4.5 for western Canada (B. napus) was reduced by 67% of the normal value because the stands reported by Van Deynze et al. (1992) were only 67% of those reported by Morrison et al. (1992).

[b] The mean of simulated yields for 1985, 1986, and 1987 (years that weather data was available for) were compared with the mean of measured yields from 1986, 1987, and 1990.

[c] Westar canola was simulated; the same soil as reported by Van Deynze et al. (1992) was used.

[d] Yields were reported for two different sites in 1986.

from Ives (1985), Kenyon (1987), and Dozois (1991). Harvest dates were unavailable for the sites so 100-day maturity was assumed for spring wheat and 93-day maturity was assumed for canola. The canola maturity time is the average reported for Brandon, Manitoba. Potential heat units of 950 for canola and 1,200 for spring wheat were also input as recommended by Shaykewich (1993).

Yield results are shown in Tables 31 and 32 for a six-year "rotation" of canola and wheat grown on Newdale soil at Minnedosa, Manitoba for three fertilizer treatments (A, B, and C) and the two levels of erosion (0 and 20 cm). In actuality, these crops were grown on separate plots from year to year and thus were not truly grown in rotation (canola is not cropped following a previous canola year to avoid disease problems). The predicted yields for 1983 in Table 32 are roughly a factor of 3 greater than those reported in Table 31, reflecting the impact of not accounting for initial nitrate levels in the soil profile. The same effect can be seen for 1984, except for treatment C, where the predicted yield in Table 31 was essentially equal to its counterpart in Table 32 because nitrogen fertilizer was applied. The effect of simulated erosion is shown for treatment A in both tables, where yields were reduced dramatically for most years. Application of nitrogen generally restored the predicted yields to full potential for both the noneroded and eroded treatments in Tables 31 and 32. Little effect was predicted by increasing fertilizer amounts from treatment B to C; more response to this step is evident for the measured yields. In general, EPIC tends to overpredict the yield in response to fertilizer application for all the treatment combinations simulated. The accuracy of the predicted yields across treatments and years is variable; it completely misses the failed yields reported for 1988. However, the

Table 31. Comparison of observed and predicted (EPIC) yields for noneroded and eroded Newdale soil at Minnedosa, Manitoba[a] without accounting for initial soil nitrate levels

Noneroded

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1983	wheat	0-0	0-20	0-45	1.2	1.2	1.2	2.9	2.8	2.6
1984	wheat	0-0	0-10	90-45	1.6	1.6	3.2	2.6	2.6	3.1
1985	canola	0-0	100-20	150-40	0.7	1.9	1.9	1.7	1.9	2.1
1986	canola	0-0	100-20	200-40	1.0	3.8	3.9	1.4	1.9	2.1
1987	wheat	0-0	100-45	200-90	1.1	3.7	3.7	2.0	3.3	3.6
1988[c]	canola	0-0	100-20	200-40	1.1	3.2	3.2	0.0	0.0	0.0

Eroded soil (20 cm artificially scraped away)

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1983	wheat	0-0	0-20	0-45	0.8	0.8	0.8	1.7	1.7	1.5
1984	wheat	0-0	0-10	90-45	1.0	1.0	3.2	1.8	2.1	2.9
1985	canola	0-0	100-20	150-40	0.4	1.9	1.9	0.8	2.3	2.6
1986	canola	0-0	100-20	200-40	0.5	3.7	3.8	0.7	1.5	1.8
1987	wheat	0-0	100-45	200-90	0.5	3.7	3.7	1.1	3.0	3.5
1988[c]	canola	0-0	100-20	200-40	0.5	3.0	3.0	0.0	0.0	0.0

[a] Simulations performed using daily historical weather data (1983-88) from the Minnedosa, Manitoba climate station.

[b] The number preceding the dash is nitrogen, while the number following the dash is phosphorous.

[c] The 1988 canola crop failed due to lack of moisture.

Table 32. Comparison of observed and predicted (EPIC) yields for noneroded and eroded Newdale soil at Minnedosa, Manitoba[a] while accounting for initial soil nitrate levels

Noneroded

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1983	wheat	0-0	0-20	0-45	2.0	3.9	3.9	2.9	2.8	2.6
1984	wheat	0-0	0-10	90-45	1.7	3.1	3.2	2.6	2.6	3.1
1985	canola	0-0	100-20	150-40	0.6	1.9	1.9	1.7	1.9	2.1
1986	canola	0-0	100-20	200-40	1.0	3.8	3.9	1.4	1.9	2.1
1987	wheat	0-0	100-45	200-90	1.4	3.7	3.7	2.0	3.3	3.6
1988[c]	canola	0-0	100-20	200-40	1.1	3.2	3.2	0.0	0.0	0.0

Eroded soil (20 cm artificially scraped away)

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1983	wheat	0-0	0-20	0-45	1.7	3.9	3.9	1.7	1.7	1.5
1984	wheat	0-0	0-10	90-45	1.0	0.9	3.1	1.8	2.1	2.9
1985	canola	0-0	100-20	150-40	0.3	1.9	1.9	0.8	2.3	2.6
1986	canola	0-0	100-20	200-40	0.4	3.7	3.9	0.7	1.5	1.8
1987	wheat	0-0	100-45	200-90	0.6	3.7	3.7	1.1	3.0	3.5
1988[c]	canola	0-0	100-20	200-40	0.5	3.0	3.0	0.0	0.0	0.0

[a] Simulations performed using daily historical weather data (1983-88) from the Minnedosa, Manitoba climate station.

[b] The number preceding the dash is nitrogen, while the number following the dash is phosphorous.

[c] The 1988 canola crop failed due to lack of moisture.

key trends of yield reduction due to erosion and improved yields from fertilizer treatments, including overcoming the effects of erosion, are correctly reflected.

The effects of the accounting for initial nitrate levels were minimal for the Waskada soil at Waskada, Manitoba as shown in Tables 33 and 34. There are only slight increases for four of the twelve treatment combinations tested in EPIC. Predicted yield response to erosion and fertilizer trends are very similar to those shown in Tables 31 and 32, including yield output for 1988 when canola failed again. It is noted that canola yields were obtained for the other four sites in 1988 that are discussed by Smith and Shaykewich (1990). Further investigation is required to better understand why the model is not correctly predicting the failed yields.

B.2. Testing for Long-Term Rotations at Swift Current

Additional testing of the EPIC crop growth model was performed for two long-term rotation data sets available from the Swift Current, Saskatchewan Agriculture Canada Research Station (Zentner 1993). Simulated EPIC yields are compared with measured yields at this site for 25-year continuous wheat and wheat-fallow rotations in Tables 35 and 36, respectively. Mixed accuracy is again seen in the predictions for individual years. In some years, the model predicted exactly or close to the actual measured yield. In other years, the estimated yield was not very close to the measured yield.

The average yield predicted by EPIC for continuous wheat was 1.4 t/ha which was very close to the historical average of 1.3 t/ha. The wheat-fallow average yield was 1.5 t/ha, which was 0.5 t/ha below the historical long-term average. EPIC estimated an average of

Table 33. Comparison of observed and predicted (EPIC) yields for noneroded and eroded Waskada soil at Waskada, Manitoba[a] without accounting for initial soil nitrate levels

Noneroded

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1986	canola	0-0	100-20	200-40	1.1	1.4	3.1	2.2	2.6	2.7
1987	wheat	0-0	100-45	200-90	1.4	2.5	2.6	2.3	1.9	2.3
1988[c]	canola	0-0	100-20	200-40	1.0	2.3	2.3	0.0	0.0	0.0

Eroded soil (20 cm artificially scraped away)

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1986	canola	0-0	100-20	200-40	0.8	1.1	3.2	1.1	1.3	2.0
1987	wheat	0-0	100-45	200-90	0.8	2.6	2.6	1.3	2.0	2.3
1988[c]	canola	0-0	100-20	200-40	0.5	2.4	2.4	0.0	0.0	0.0

[a] Simulations performed using daily historical weather data (1986-88) from the Delorain, Manitoba climate station.

[b] The number preceding the dash is nitrogen, while the number following the dash is phosphorous.

[c] The 1988 canola crop failed due to lack of moisture.

Table 34. Comparison of observed and predicted (EPIC) yields for noneroded and eroded Waskada soil at Waskada, Manitoba[a] while accounting for initial soil nitrate levels

Noneroded

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1986	canola	0-0	100-20	200-40	1.4	1.5	3.1	2.2	2.6	2.7
1987	wheat	0-0	100-45	200-90	1.3	2.5	2.6	2.3	1.9	2.3
1988[c]	canola	0-0	50-0	100-20	1.0	2.3	2.3	0.0	0.0	0.0

Eroded soil (20 cm artificially scraped away)

Year	Crop	Fertilizer treatments (N-P, kg/ha)[a]			Predicted yields			Observed yields		
		A	B	C	A	B	C	A	B	C
1986	canola	0-0	100-20	200-20	1.1	1.1	3.2	1.1	1.3	2.0
1987	wheat	0-0	100-45	200-90	0.8	2.6	2.6	1.3	2.0	2.3
1988[c]	canola	0-0	50-0	100-20	0.5	2.4	2.4	0.0	0.0	0.0

[a] Simulations performed using daily historical weather data (1986-88) from the Delorain, Manitoba climate station.

[b] The number preceding the dash is nitrogen, while the number following the dash is phosphorous.

[c] The 1988 canola crop failed due to lack of moisture.

Table 35. Comparison of simulated and measured yields for continuous wheat over a 25-year period for plot 38 at the Swift Current, Saskatchewan Agriculture Canada Research Station

	Simulated yields (t/ha)	Measured yields (t/ha)	Applied nitrogen (kg/ha)	Applied P_2O_5 (kg/ha)[a]
67	1.2	1.4	38.56	21.52
68	1.1	0.5	27.35	21.52
69	2.4	1.2	27.35	21.52
70	1.1	1.3	4.93	21.52
71	1.7	1.0	27.35	21.52
72	0.6	1.3	4.93	21.52
73	0.4	1.1	4.93	21.52
74	1.3	1.8	21.75	21.52
75	1.3	1.2	21.75	21.52
76	1.2	1.4	21.75	21.52
77	2.7	2.0	55.38	24.66
78	1.1	1.2	55.38	24.66
79	1.3	1.4	38.56	24.66
80	2.7	0.7	55.38	22.87
81	1.9	1.6	38.56	29.66
82	1.3	2.2	21.75	22.87
83	1.3	1.6	22.00	22.87
84	0.8	0.3	38.56	22.87
85	0.5	0.5	4.93	22.87
86	1.4	2.1	21.75	22.87
87	1.4	1.0	37.33	17.15
88	1.8	0.0	56.39	22.87
89	0.9	1.5	3.70	17.15
90	1.8	1.6	26.57	17.15
91	2.8	3.0	53.70	17.15
Average yield	1.4	1.3		

[a] The actual phosphorous input to the model was the amount listed multiplied by 0.436.

Table 36. Comparison of simulated and measured yields for a wheat-fallow rotation over a 25-year period for plot 25 at the Swift Current, Saskatchewan Agriculture Canada Research Station

	Simulated yields (t/ha)	Measured yields (t/ha)	Applied nitrogen (kg/ha)	Applied P_2O_5 (kg/ha)[a]
67	0.6	1.4	4.93	21.52
68	0.0[b]	0.0[b]	0.0	0.0
69	2.2	2.0	4.93	21.52
70	0.0	0.0	0.0	0.0
71	2.6	1.9	4.93	21.52
72	0.0	0.0	0.0	0.0
73	0.7	1.2	4.93	21.52
74	0.0	0.0	0.0	0.0
75	1.7	1.7	4.93	21.52
76	0.0	0.0	0.0	0.0
77	1.5	2.5	4.93	24.66
78	0.0	0.0	0.0	0.0
79	1.0	2.0	4.93	24.66
80	0.0	0.0	0.0	0.0
81	1.8	3.0	4.93	22.87
82	0.0	0.0	0.0	0.0
83	1.8	2.2	4.93	22.87
84	0.0	0.0	0.0	0.0
85	0.7	0.7	4.93	22.87
86	0.0	0.0	0.0	0.0
87	1.4	2.0	3.70	17.15
88	0.0	0.0	0.0	0.0
89	1.7	2.0	3.70	17.15
90	0.0	0.0	0.0	0.0
91	1.4	3.0	4.93	22.87
Average yield	1.5	2.0		

[a] The actual phosphorous input to the model was the amount listed multiplied by 0.436.

[b] Zero yields in the even years reflect fallow conditions.

41 nitrogen stress days for the wheat-fallow rotation. This would indicate that the model over-penalized the wheat yields for lack of nitrogen in the fallow rotation.

C. Testing of the EPIC 3090 Wind Erosion Model

An additional test was performed for the noneroded Newdale soil at Minnedosa, Manitoba for the canola wind erosion parameters BW_1, BW_2, and BW_3 (Tables 7 and 27). The BW parameters are determined as a function of flattened wheat straw, as discussed by Troeh et al. (1991). The runs were performed with the Brandon, Manitoba wind array. The BW_1, BW_2, and BW_3 were set at: (1) 3.39, 3.39, and 1.61 for run 1 and (2) 1.27, 0.6, and 0.73 for run 2 and run 3. The BW parameters for run 1 are those normally assumed for wheat while the BW values for run 2 and run 3 are those that will actually be used for canola for the GRIP/NISA analyses. No fertilizer was applied (treatment A Table 32) for the first two runs while fertilizer treatment C as given in Table 32 was assumed for run 3.

The results in Table 37 show that there was essentially no difference in the predicted wind erosion yields for 1983 across the three different simulations. However, significant shifts occurred between runs for the estimated wind erosion during the remaining years. Erosion rates shifted upward 100 and 64 percent for canola in 1985 and 1986 between run 1 and 2, reflecting the impact of lower residue amounts resulting from the lower BW values used in run 2. On the other hand, the lowest wind erosion rates were estimated for run 3, in spite of the lower BW values. This was due to the increased biomass and residue levels that resulted from the fertilizer inputs each year.

Table 37. Comparison of wind erosion values for a six-year rotation on Newdale soil at Minnedosa, Manitoba for two different sets of canola wind erosion crop parameters and two fertilizer levels[a,b]

		Wind erosion Y_w (t/ha) and yield (t/ha)					
		Run 1[c]		Run 2[d]		Run 3[e]	
Year	Crop	Y_w	Yield	Y_w	Yield	Y_w	Yield
1983	wheat	0.19	2.0	0.20	2.0	0.22	3.9
1984	wheat	1.99	1.7	1.99	1.7	1.11	3.2
1985	canola	0.46	0.6	0.92	0.6	0.44	1.9
1986	canola	1.88	1.0	2.93	1.0	1.25	3.9
1987	wheat	0.80	1.4	1.29	1.4	0.20	3.7
1988	canola	0.45	1.1	0.52	1.1	0.24	3.2

[a] The Brandon, Manitoba wind array was used.

[b] Noneroded soil and initial nitrate levels (as discussed in section IV.B.1) were simulated.

[c] Run 1: $BW_1 = 3.39$, $BW_2 = 3.39$, $BW_3 = 1.61$ (see Table 2 for description of BW_1, BW_2, and BW_3); no fertilizer was applied (treatment A as given in Table 31).

[d] Run 2: $BW_1 = 1.27$, $BW_2 = 0.6$, $BW_3 = 0.73$; same fertilizer level as Run 1.

[e] Run 3: $BW_1 = 1.27$, $BW_2 = 0.6$, $BW_3 = 0.73$; fertilizer treatment C as given in Table 31.

A second test of the EPIC 3090 wind erosion model was performed for southern Alberta conditions using input files developed for the Del Bonita site as described by Izaurralde et al. (1992). Figure 13 shows the average wind erosion yields predicted by month over a 30-year period for five different management and cropping sequence combinations using the Del Bonita input files. The simulations were performed in EPIC 3090 except for the FWCH3030 run, which was made in EPIC 3030. A noble plow was used for the fallow portion of the unfertilized fallow-spring wheat (FW) rotation that has a mixing efficiency of 10 percent (see variable EMX in Table 10 for the Noble plow), meaning that only 10 percent of the residue is buried in each pass. A sweep-chisel was used for the spring wheat portion of the FW rotation, as well as for the continuous spring wheat (CW) rotation, the fertilized (61.0 kg/ha N) continuous spring wheat (CWFE) rotation, and the other two fallow wheat rotations (FWCHIS and FWCH 3030). The mixing efficiency of the sweep-chisel is 33 percent, which results in more residue being mixed into the soil profile after each pass as compared to the Noble plow. Four passes of both implements were performed for the fallow periods of the rotations.

The results show that the greatest amount of erosion occurred during the spring and winter months, which is consistent with expectations. The least amount of annual erosion was predicted for the FWCH3030 rotation, the only one performed in EPIC 3030. In contrast, EPIC 3090 predicted that approximately 25 t/ha of wind erosion would occur for the exact same input file on an annual basis, several times the amount estimated with EPIC 3030. The estimated annual wind erosion rate for the unfertilized continuous wheat file (CW) was nearly as high as that estimated for the FWCS rotation. This is due primarily to the decreased biomass and residue

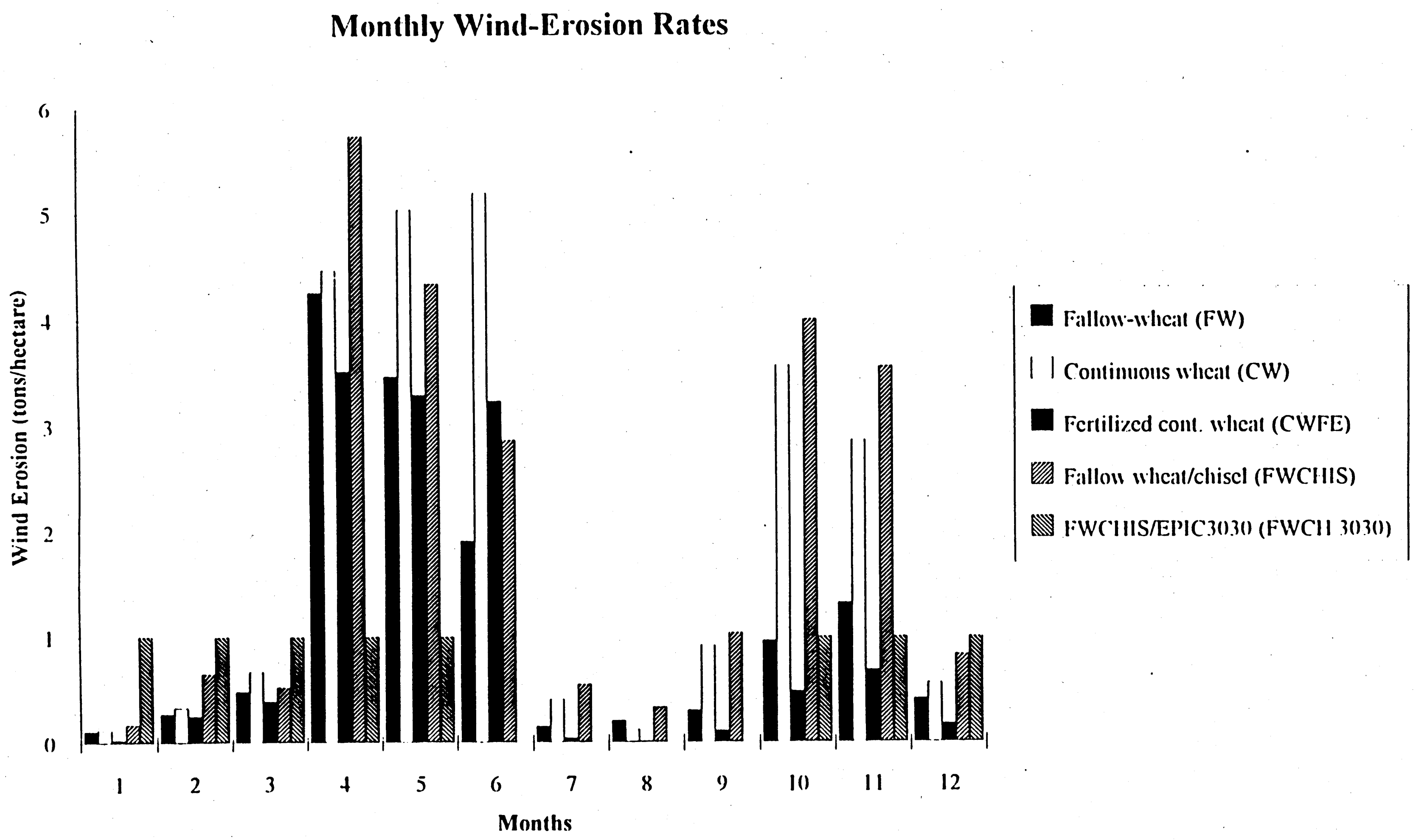

Figure 13. Comparison of wind erosion values by month in southern Alberta with EPIC 3090 (Notes: Noble plow used for fallow in FW; sweep-chisel used for all other fallow and wheat; 61.0 kg/ha N used in CWFE; FWCH3030 was run in EPIC 3030).

of the CW rotation (the average estimated CW biomass was 1.8 t/ha compared to 3.6 t/ha estimated for the FWCS rotation). On an annual basis the FW rotation resulted in less erosion than the CW and FWCS rotations due to the use of Noble plow during the fallow years which kept much of residue on the soil surface. However, the erosion rates for the continuous wheat scenario dropped below the FW levels when fertilizer was applied (CWFE), due to the increased biomass and residue that was produced by the wheat crop.

The results of these simulations cannot be confirmed with measured data. However, wind erosion data collected by Larney (1993) for a summer fallow site with no residue coverage near Lethbridge, Alberta, during the period April 1991 to May 1992, confirms that wind erosion yields can be very high in southern Alberta. A total of 144 t/ha of soil was lost over 16 events during this period. The erosion rate measured for the largest event was 32 t/ha. These data indicate that the results from EPIC 3030 are too low for the region and that the EPIC 3090 output is more in line with expectations. This view is confirmed by Tajek (1993), who applied previous versions of EPIC for simulating wind erosion in southern Alberta. In his opinion, the new model is producing much improved estimates of wind erosion.

Further tests of the EPIC 3090 wind erosion model indicate that it is particularly sensitive to the value used for the "power parameter of the modified exponential wind speed distribution", which can range from 0.2 to 0.6. The annual erosion amounts shown in Figure 13 were reduced by approximately a factor of 2 when this parameter was changed from 0.6 to 0.5. While a value of 0.5 is typically recommended, it appears that setting this parameter to a value of 0.6 may produce more accurate results for western Canada conditions.

V. EPIC STRENGTHS AND WEAKNESSES

The major strength of EPIC is its comprehensive ability to simulate the affects of water and wind erosion upon soil productivity for a vast range of management, cropping sequence, soil, and climate combinations. This comprehensive nature is further strengthened by routines that simulate movement of nutrients and pesticides, and other enhancements such as a built-in weather generator and an input file preprocessor. It is thus possible to simulate many different agricultural environmental scenarios in support of policy analyses within a single modelling package.

Paradoxically, this comprehensive structure also proves to be a key weakness in applying EPIC for two main reasons. First, the model requires a large set of data inputs; while many of the data inputs can be set to default values (or even ignored), it is still a major task to gather all of the necessary inputs. Second, researchers representing multiple disciplines are required for the testing of the different submodels that are contained in EPIC. This can be a difficult task, especially when there are limited data sets to test different components (as indicated in section IV).

The strength and weakness paradox due to EPIC's comprehensive nature is particularly true regarding its crop growth model. The generic crop growth model used in EPIC provides the ability to simulate long-term soil productivity impacts for a variety of crops, and is very flexible in handling rotations. However, the crop growth model is designed to predict long-term averages and is not as adept at predicting absolute and year-to-year variability in yields. This was reflected in the calibration results documented above.

This underscores the point made earlier that EPIC (and similar models) should be used primarily to provide relative comparisons of soil degradation, soil productivity, and so forth rather than relying on the absolute numbers that are produced by the model. This objective is well summarized by Leonard and Knisel (1990), who played key roles in the development of the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel et al. 1982) and the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al. 1987):

> Since models are only mathematical approximations and presentations of the real world, and since the amount and quality of the data are limited by practical considerations, no model in existence, when applied to natural watershed systems, can be proven to provide absolutely correct output or even output with a high level of statistical confidence. Models such as CREAMS and GLEAMS are recommended only for making comparative assessments and not for absolute prediction. That is, model output is to be used, along with other information and considerations, in making decisions or choosing alternatives. The final test is not so much whether the model outputs are numerically correct but whether the outputs lead to the correct decision.

This summary definitely holds true for EPIC in this study. First of all, there is uncertainty about several of the data inputs such as the estimates of the landscape slope lengths, especially when the model is being used for regional applications rather than at a field scale. This undermines the reliability of the model to produce accurate absolute values. Second, accurate absolute predictions require careful calibration and alignment of all important variables in the model for every condition, which generally is not known. Instead, the relative changes from established baseline values are reported for a change in one or two key parameters, such as tillage or crop rotation, which is much easier to validate.

It is stressed that EPIC output is in the form of absolute numbers. The construction of metamodels from EPIC simulations are based on these absolute outputs and the absolute values of the input data provided to the model. Previous experience with constructing metamodels based on modeling results with the USEPA Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations (RUSTIC) model (Dean et al. 1989) showed that the metamodels accurately reflected the absolute output of the model based on standard statistical tests (Bouzaher et al. 1993). Water erosion metamodels with R^2 values as high as 0.93 are also being developed based on current applications with EPIC by Lakshminarayan (1993) for a portion of the U.S. Midwest.

From the standpoint of valid statistical criteria, the construction of metamodels based on the current level of EPIC performance, that accurately mimic the model output, is not a problem. However, there is still the question as to how well EPIC is reflecting reality in the first place. While we stress the use of EPIC for relative comparisons, we also emphasize the importance of testing and calibrating the model based on measured data to the fullest extent possible to improve its accuracy. This is essential in ensuring that the model is indeed reflecting reality and providing the right kind of relative comparisons. The limited tests performed for this study show that the model tracks most of the important processes in a logical way and produces accurate average yields. However, deficiencies in year-to-year yield estimates were noted at several of the test sites and in general there is a lack of data to validate some of the most important processes such as wind and water erosion. Thus, additional testing of the EPIC model is required in order to calibrate it to produce the most accurate output possible for Western Canadian conditions.

Regardless of how much testing is performed, it is well to keep the following point by Leonard and Knisel (1990) in mind:

> The ultimate goal is the development of a model to give accurate predictions in the sense of absolute quantities. However, user or management models that can be proven to predict with absolute accuracy are not on the immediate horizon. Complex research-type models, even if much more accurate than management models, will require a gargantuan effort in validation and comparison before users can be convinced that the additional accuracy justifies the effort.

A separate but related issue is the fact that while EPIC is a field-scale model, it is being applied at the landscape polygon and ARA regional levels for this study. The full implications of this "scaling-up," which will be accomplished with the metamodels, are not clear. It is assumed that the model will accurately reflect the key processes that are occurring on a landscape basis. However, the output must be aggregated over the region which will undoubtedly introduce biases into the final results. Further research is also needed to better understand the effects of applying EPIC at different scales.

A. Recommendations for Further Research

Several recommendations can be made based on the strengths and weaknesses of EPIC discussed above and on the development of the environmental database that are described in this report. These recommendations are as follows:

1.) Identify additional data sets that can be used to test the EPIC erosion submodels, hydrology submodel, crop growth model, and other important components. To our knowledge, measured wind erosion data are being collected for the first time in Western Canada (Larney 1993). Shaykewich (1993) has also described water erosion data sets that have been collected in Manitoba that may be useful for EPIC validation. Additional crop rotation data at Swift Current and other sites is available to test the yield output of EPIC. These and possibly other data sets could be used to further test and refine EPIC input parameters for the Prairie Provinces.

2.) Assemble an interdisciplinary team to test the different EPIC submodels for Western Canada conditions. This team should be comprised mainly of experts from the region and should include the model developers in an advisory capacity. This effort could even involve modifying the model code to more accurately reflect conditions in the Prairie Provinces.

3.) In conjunction with recommendations 1.) and 2.), additional field experiments should be set up that are specifically designed to test different EPIC submodels.

4.) A comprehensive review of the landform and soil layer data is warranted by a team of experts representing both the Prairie Provinces and the Centre for Land and Biological Resources Research in Ottawa. Key data that should be reviewed include the estimated landscape slope lengths and soil hydrologic groups; other components of the data should also be reviewed.

5.) Similar to 4.), further review of the weather data is warranted to ensure its accuracy.

6.) A review of available data on the effects of tillage on yield is needed. This would be useful to examine if EPIC is accurately reflecting tillage impacts on yield in the Prairie Provinces.

VI. SUMMARY

An environmental modelling system is being constructed around the EPIC model that will be interfaced with an economic component (RS-CRAM) within an integrated modelling system to analyze agricultural policies such as GRIP and NISA. This environmental modelling system will be used to develop environmental and yield distribution metamodels (response functions) that will be used in the actual policy analysis simulations. The EPIC model was developed to assess the long-term impacts of erosion on soil productivity (crop yield) for the 1985 USDA-RCA analysis. Since that time, the applications of the model have expanded to include other analyses such as assessment of water quality. The EPIC model is built around a main program that controls the flow of data to its ten major subcomponents: (1) weather, (2) hydrology, (3) erosion, (4) nutrient cycling, (5) soil temperature, (6) crop growth, (7) tillage, (8) plant environment control, (9) pesticide fate, and (10) economic crop budgets.

An environmental database has been constructed for EPIC that consists of: (1) soil layer and landform data in separate databases for each of the Prairie Provinces, (2) ARA 31-year daily historical weather data (precipitation and maximum and minimum temperature) in EPIC format, (3) EPIC weather generator tables for each ARA, and (4) EPIC wind arrays for selected climate stations in Alberta, Manitoba, and Saskatchewan. The soil layer and landform data are applicable at both the landscape polygon and ARA levels. Data containing the percentage of each polygon that is cultivated have been received to aggregate the environmental results to the RS-CRAM region level.

Calibration and testing of the EPIC model has been performed for selected sites in the Prairie Provinces and U.S. Northern Great Plains. Calibration of crop parameters has been performed for spring wheat, barley, canola, fall rye, and different grasses. Comparisons of predicted yields with measured data show that the model is producing reasonable yield estimates for different crops that are grown in Western Canada. Yield estimates by EPIC show that it is definitely better at predicting long-term average yields as compared with individual crop year yields, a result that agrees with results obtained by Beckie and Moulin (1992). However, the model does accurately reflect key trends such as crop response to fertilizer and productivity response to soil erosion.

The results also indicate that the model is a reliable predictor of relative environmental impacts (between different scenarios) for economic-environmental analyses at the ARA level in the Prairie Provinces. We affirm, however, the recommendation by Izaurralde et al. (1992) that EPIC results be used to provide relative comparisons of environmental impacts as opposed to absolute values.

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