Regional Estimation of Soil Carbon and Other Environmental Indicators Using EPIC and i_EPIC

Philip W. Gassman, Todd Campbell, César Izaurralde,
Allison M. Thomson, and Jay D. Atwood

Technical Report 03-TR 46
April 2003

Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070
www.card.iastate.edu

Philip Gassman is an assistant scientist and Todd Campbell is a systems analyst, both in the Resource and Environmental Policy Division, Center for Agricultural and Rural Development, Iowa State University.

César Izaurralde is a soil scientist and Allison M. Thomson is an environmental scientist, both with the Joint Global Change Research Institute, University of Maryland, and Pacific Northwest National Lab, College Park, Maryland.

Jay Atwood is an agricultural economist with the Natural Resource Conservation Service, Resource Assessment Division, U.S. Department of Agriculture, Temple, Texas.

This publication is available online on the CARD website: *www.card.iastate.edu*. Permission is granted to reproduce this information with appropriate attribution to the authors and the Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa 50011-1070.

For questions or comments about the contents of this paper, please contact Philip Gassman, 560E, Heady Hall, Iowa State University, Ames, IA 50011-1070; Ph: 515-294-6313; Fax: 515-294-6336; E-mail: pwgassma@iastate.edu.

Iowa State University does not discriminate on the basis of race, color, age, religion, national origin, sexual orientation, sex, marital status, disability, or status as a U.S. Vietnam Era Veteran. Any persons having inquiries concerning this may contact the Director of Equal Opportunity and Diversity, 1350 Beardshear Hall, 515-294-7612.

Abstract

Computer models are important tools for assessing regional carbon sequestration and other environmental impacts of agricultural management practices. The Environmental Policy Integrated Climate (EPIC) model is a very flexible model that has been used to make a wide range of field- and regional-scale environmental assessments. Large regional-scale applications of EPIC and similar models can require thousands of runs, resulting in a huge data management task. To address this problem, the Center for Agricultural and Rural Development (CARD) has developed an interactive EPIC (i_EPIC) software package that provides an automated approach to executing large sets of EPIC simulations. Overviews of both the latest EPIC version and the i_EPIC software package are presented. We also present examples of regional applications using both EPIC and i_EPIC conducted by the Resource and Environmental Policy Division of CARD, by the Joint Global Change Research Institute of the University of Maryland and the Pacific Northwest National Laboratory, and by the Resource Assessment Division of the Natural Resources Conservation Service, U.S. Department of Agriculture.

Keywords: environmental indicators, modeling, regional analyses, software interface, soil carbon.

REGIONAL ESTIMATION OF SOIL CARBON AND OTHER ENVIRONMENTAL INDICATORS USING EPIC AND I_EPIC

Introduction

Resource questions associated with agricultural production are becoming increasingly complex. Decisionmakers must balance the requirements of the agricultural system in order to provide an abundant and affordable food supply with the need to protect water quality, mitigate carbon loss to the atmosphere, and prevent other negative environmental externalities. Flexible tools that can provide reliable estimates of economic and/or environmental impacts for a wide combination of cropping and management systems, climatic conditions, soil types, and landscapes are vital to achieving this balance. These tools include simulation models, which can be used for estimating a variety of environmental indicators at the field, watershed, and/or regional scales.

One of the most widely used simulation models for agricultural policy analysis is the Erosion Productivity Impact Calculator (EPIC) model (Williams 1990; Williams 1995), originally developed by the U.S. Department of Agriculture (USDA) and now maintained by the Texas A&M Blacklands Research Center. EPIC is a field-scale model that can be adapted to a large range of crop rotations, management practices, and environmental conditions. The original version of the model was designed primarily to assess the impacts of soil erosion on crop productivity (Williams, Jones, and Dyke 1984). A more recent version of the model is called Environmental Policy Integrated Climate (Mitchell et al. 1996), reflecting the evolution of the tool to include estimation of a variety of environmental indicators. Example applications include estimations of

- soil erosion from water (Chung et al. 1999; Phillips et al. 1993) and wind (Potter et al. 1998);
- climate change impacts on crop yield (Stockle et al. 1992; Brown and Rosenberg 1999) and soil erosion (Favis-Mortlock et al. 1991; Lee, Phillips, and Dodson 1996)**;**

- edge-of-field nutrient losses from fertilizer and/or animal manure applications (Edwards et al. 1994; Bernardos et al. 2001; Chung et al. 2001);
- edge-of-field losses from pesticide applications (Williams, Richardson, and Griggs 1992); and
- soil carbon sequestration (Apezteguía et al. 2002; Izaurralde et al. 2002).

EPIC has also proven adaptable for large regional analyses, for example, estimation of water and wind erosion for the Canadian Prairie Provinces (Izaurralde et al. 1997; Lakshminarayan et al. 1996), and prediction of nutrient losses and other indicators for the 12-state North Central region (Wu and Babcock 1999; Babcock et al. 1998; Gassman et al. 1998). These regional applications typically require thousands of EPIC simulations, resulting in a formidable task of managing the input and output data. Software initially was constructed at the Center for Agricultural and Rural Development (CARD) on a UNIX platform to automate construction of the input data, execution of simulations, and storage of desired output data for large sets of EPIC simulations. This initial approach has been refined into a user-friendly, PC-based software package titled “Interactive EPIC” or i_EPIC. The i_EPIC software allows the user to handle both input and output data in a consistent database structure for EPIC simulation sets numbering in the tens of thousands, as well as providing diagnostic and editing tools in both the database and the windows interface. Overviews of both EPIC and i_EPIC are presented in this paper, with particular emphasis on how EPIC can be executed within i_EPIC to produce regional estimates of environmental indicators. Example applications of the system by CARD’s Resource and Environmental Policy division (CARD-REP) and other user groups also are described.

Overview of EPIC

EPIC is a field-scale model designed to simulate drainage areas of up to 100 ha that are characterized by homogeneous weather, soil, landscape, crop rotation, and management system parameters. It operates on a continuous basis using a daily time-step and can perform long-term simulations of hundreds of years. A generic crop growth routine that facilitates simulation of crop rotations using parameters developed for nearly 100 crops is used in the model. Up to 12 crops and/or other plants also can be simulated simultaneously, allowing inter-crop, crop-weed, and similar scenarios to be performed. Tillage effects on surface residue, soil bulk density, and mixing of residue and nutrients in the soil plow layer is accounted for in the model; these and other factors also are incorporated into the model's estimations of water and wind erosion. Multiple nutrient and pesticide applications can be included in a single simulation, and edge-of-field leaching, runoff, and/or volatilization losses can be output (depending on which chemical is being simulated). Table 1 lists the major components that are included in EPIC1015[1], the latest version of the model.

EPIC1015 includes an improved carbon cycling routine (Izaurralde et al. 2002) that is based on the approach used in the Century model developed by Parton et al. (1994). In this updated routine, carbon (C) and nitrogen (N) compounds are simulated within three soil pools of increasing turnover time: biomass, slow, and passive. However, only two surface litter pools (biomass and slow) are simulated in EPIC1015, instead of the three used in Century. Other differences between EPIC1015 and Century include (1) using existing EPIC equations to simulate movement of organic material from the surface litter

TABLE 1. Major components included in EPIC version 1015

Component	Comments	Key Inputs or Simulated Functions
Climate	Daily measured and/or generated data can be input	Precipitation, max. and min. temperature, solar radiation, windspeed, relative humidity
Management	Can simulate many different tillage and fertilizer levels	Fertilizer or manure, lime, pesticides, irrigation, drainage, tillage
Hydrology	Two options for infiltration; four for evapotranspiration	Surface runoff, infiltration, lateral subsurface flow, evapotranspiration, snow melt
Erosion	Six options for water erosion	Both water and wind erosion are simulated
Nutrients	Routines for nitrogen, phosphorus, and potassium	Crop uptake, leaching, surface runoff, mineralization, and other processes
Carbon	Century-based routines only in EPIC1015	Biomass, slow, and passive pools are simulated in soil profile
Crop growth	Generic routine; very flexible for simulating rotations	Crop biomass and yields; inputs developed for ~100 crops
Soil temperature	Used in nutrient cycling and hydrology routines	Daily average soil temperature
Economics	Simple crop budgets	Fixed and variable costs

Note: Component categories are adapted from those described by Williams (1990).

to deeper soil subsurface layers and to calculate C and N transformation rates, and (2) determining crop lignin concentration during a growing season as a sigmoidal function of plant development. Losses of C and N by leaching or gaseous forms are accounted for in EPIC1015 in a way similar to that of Century. Further details on the EPIC1015 carbon cycling methodology are presented in Izaurralde et al. 2001, 2002.

At present, the latest publicly released version of the model is EPIC0250. Release of EPIC1015 is anticipated in the near future, after further testing of the model is completed. Both versions of the model, as well as two older EPIC versions, can be applied in the current i_EPIC software, as described in the following section.

Overview of i_EPIC

The basic philosophy of the i_EPIC approach is to manage both the input and output data of a large set of EPIC simulations within a single database. This requires converting all existing data from ASCII files and other file formats into Microsoft Access®, the database program that has been selected for the i_EPIC system. Thus, it is incumbent upon the i_EPIC user to develop methods of processing desired input data into the proper database structure required for i_EPIC.

A general schematic of the data flows for the i_EPIC system are shown in Figure 1. Soil and landscape, climate, cropping system, and management (tillage, fertilizer, etc.) are the main categories of input data. Preprocessing of input data is performed to translate the existing data files into the Access database format. Twelve tables are constructed that contain the required input data for i_EPIC and EPIC (Table 2); the exact inputs included in some of the tables are dependent on the version of the model being used. Once the input data have been constructed, the entire EPIC simulation set can be executed automatically within i_EPIC. Alternatively, individual runs or subsets of a simulation set can be performed. Output data for each simulation is scanned from standard EPIC output files and stored in the database (Table 2)

The i_EPIC software is accessible online by going to *http://www.public.iastate.edu/~elvis* and clicking on the i_EPIC link. Similar software can also be obtained for the Century model and Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998) via the same web page.[2] Two versions of the i_EPIC software are available for

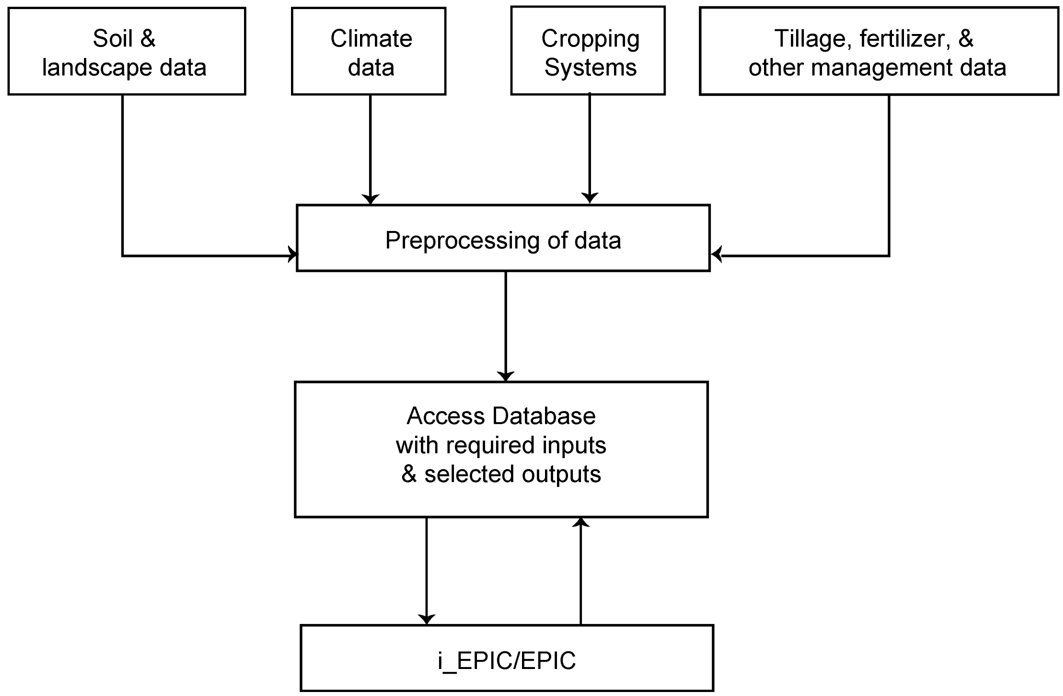


FIGURE 1. General schematic of the data processing steps required for the i_EPIC system

download, one based on Access 97 and the other on Access 2000.[3] Some documentation is provided on the web site, such as definitions of toolbar button functions, a limited set of frequently asked questions, a history of modifications to the code, and structure of the data tables. At least partial documentation is provided for all of the database tables, which can include the names used in the Access tables for each variable, the equivalent EPIC variable name, the units (if applicable), the type of variable (integer, etc.), and a description or comment. The control records table is a key table that contains data that define the characteristics of each EPIC simulation, including the crop rotation, soil type, weather station ID, and location (latitude and longitude). Some of the fields in this table are not actual EPIC inputs but pertain to the National Resources Inventory (NRI) Database (Nusser and Goebel 1997; USDA, NRCS n.d.) which is a valuable source of data for regional analyses. Data that are not used in EPIC are identified as “Not passed to EPIC” in the comments for each field.

At present, four different versions of EPIC (5300, 8120, 0250, and 1015) can be executed within i_EPIC. The executable for each of the EPIC versions is included with the i_EPIC download, except for EPIC1015 (which will be incorporated into the

TABLE 2. List of tables required for the Access database used by i_EPIC

Database Table	Description	Database Links[a]
Input data		
Control records	Characteristics for each EPIC simulation	ID; weather station ID, soil ID
Crops[b]	Standard EPIC crop parameter file	-
Fertilizer[b]	Standard EPIC fertilizer characteristics file	-
Field operations	Operation schedules for APEX opsc files	ID
Management	Management data for APEX subarea files	ID
Operations[b]	Standard EPIC machinery operations file	-
Parameters[b]	Standard EPIC miscellaneous parameter file	ID
Pesticides[b]	Standard EPIC pesticide characteristics file	-
Soil layers	Soil layer data required by subarea	Soil ID
Soils	Soil name; misc. soil data by subarea	Soil ID
Weather	Weather station; miscellaneous weather data	Weather station ID
Weather by month	Monthy weather and wind statistics	Weather station ID
Output variables	15 variables that user can select for annual output	ID
Output data		
Output[c]	Average annual results for four variables	ID
Output Annual	Annual results for up to 45 output variables	ID
Output Annual Crop Yields	Annual yields for simulated crops in each run	ID
Output Soil Carbon Nitrogen	EPIC1015 output file with C and N results	ID

[a]Codes used to link files relationally in database; ID is the ID number for each EPIC simulation.
[b]The specific variables and the total number of variables can vary for these files between EPIC versions; they are not directly linked within the relational structure of the Access database, but are linked into each EPIC simulation (e.g., the crops table via crop ID within the field operations table).
[c]This table is essentially nonfunctional at present.

download at a future point). The online documentation is oriented toward the 0250 and 1015 versions, but any of the four versions can be successfully executed within the system if the Access tables are filled with the correct inputs. This is an especially critical step regarding the miscellaneous parameter file (parameters table) because the values, definitions, and number of these parameters are in constant flux between versions. There also have been changes in some of the other input files, mostly in the form of additional new variables. For example, several new variables, highlighted in red in the online documentation, were added to the operations table for EPIC1015, and a few other new variables were added in other tables. One option that is available to help ensure that the correct inputs are used for a specific version is to first import into i_EPIC a set of input files known to work in that version, using the i_EPIC import function (under "file" on the toolbar menu). These imported inputs can then be used as a guide for constructing the inputs for a larger simulation set. A final point to note is that the Access tables include all the inputs used in all four EPIC versions; those inputs that are not relevant to a specific version are ignored when performing simulations with that version.

Once a database has been constructed, it can be read into i_EPIC using a standard Windows read function. The next step is to choose "configuration" (under "file" on the toolbar), which allows the user to pick one of the four EPIC versions that can be run with the program. The user can then elect to run a single EPIC simulation, a subset consisting of multiple runs, or the entire simulation set. There is also an option to modify some of the input variables via several pop-up screens. Other diagnostic tools for individual simulations provide the ability to plot a timeline of operations or to obtain a listing that highlights different operation categories in specific colors. Also provided are post-simulation diagnostic tools that allow the user to plot selected outputs for a single simulation or for multiple simulations.

Inputs can be manipulated in the Access database before reading them into i_EPIC. This is a more flexible option that allows the user to change one or more variables for part or all of a complete simulation set. Output diagnostics in the form of queries and simple statistics can be performed in Access; exporting the output data into other software packages such as Microsoft Excel provides additional post-simulation processing options.

Example Applications

The i_EPIC software has been used by CARD-REP primarily to support analyses performed for part of or the entire 12-state North Central region. At least two other extensive applications of the software have been performed. The first is a national assessment of agricultural practices for selected crops by the USDA's Natural Resources Conservation Service, Resource Assessment Division (NRCS-RAD). The second is an ongoing project of the Joint Global Change Research Institute (JGCRI) in which hundreds of representative farms are being developed to simulate the impacts of agricultural production practices across the globe under current and alternative climate conditions. Examples of how EPIC and i_EPIC are being used by each of these three research groups are presented next.

Application by the Center for Agricultural and Rural Development

The applications of i_EPIC by CARD-REP have been performed in the context of the Regional Agricultural Policy System (RAPS), an integrated economic and environmental modeling system (Figure 2) developed for the North Central region (Babcock et al. 1998; Gassman et al. 1998). The modeling framework is constructed around the 1992 and/or 1997 NRI databases,[4] which provide baseline land use and other data for over 366,000 “points” (typically representing areas consisting of hundreds of hectares) for the region (Figure 3). The subset of agriculturally relevant points are used to define the specific soil type, landscape, crop rotations, other land use (Conservation Reserve Program [CRP] and pastureland), tillage, tile drainage, and irrigation that are simulated in the modeling system. A second key source of input data is the USDA’s Economic Research Service (ERS) 1990-95 Cropping Practices Survey (CPS), which provides information on machinery budgets and associated costs. Climate and soil layer data are input into the system from other databases. A baseline is usually performed as the first step in analyzing one or more policy scenarios. The next step is to impose an alternative scenario(s) on the Discrete Choice Economic Model, a model that estimates production costs and returns, as well as producers’ decisions regarding tillage practice, crop rotation, and/or CRP participation for all the NRI points included in the analysis.[5] These decisions are then incorporated into the EPIC simulations for the NRI points for the same scenario.[6] The EPIC simulations are performed using i_EPIC after the required input data has been entered into the Access database tables as previously described.

An example application is described here in which three sets of 30-year EPIC1015 simulations were executed using i_EPIC for over 15,000 cropland-relevant NRI points in Iowa. This was a partial application of the RAPS system and did not include the economic model. An initial baseline was simulated for the first set of EPIC runs in which the model assumptions were based on NRI data for each point, including a mix of different tillage

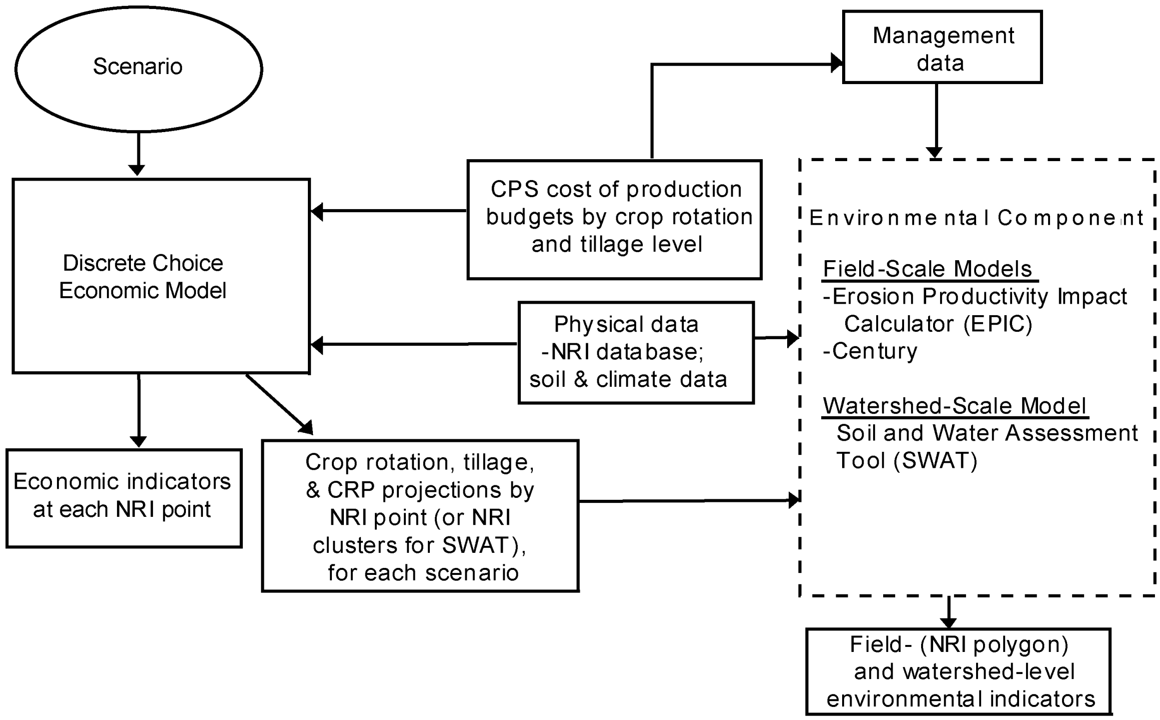


FIGURE 2. Schematic of the Regional Agricultural Policy System (RAPS)

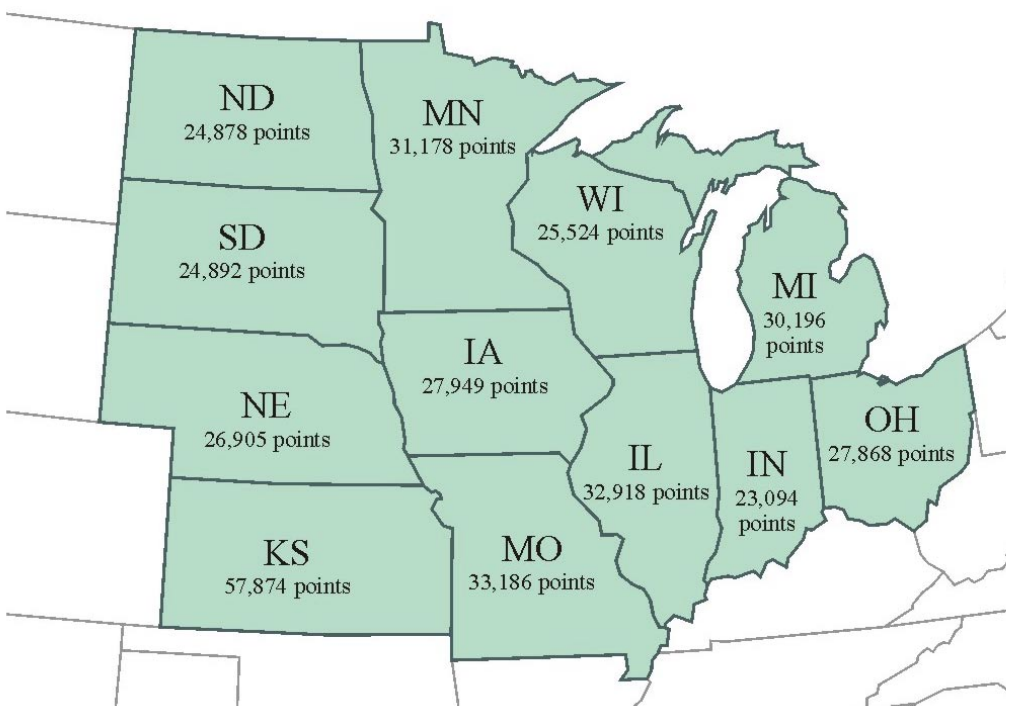


FIGURE 3. Total National Resources Inventory points in each of the North Central states

levels (ranging from no-till to conventional tillage). Two additional simulation sets were then performed: one that assumed all the NRI points were managed with conventional tillage, and another that assumed all the NRI points were managed with no-till. The soil carbon levels for each of these scenarios were then compared against the baseline, to ascertain the impacts on carbon sequestration trends of all producers in Iowa shifting into either of the two tillage extremes. The differences between the baseline and conventional tillage scenario (Figure 4) and the baseline and no-till scenario (Figure 5) are plotted using "NRI polygons," which are the smallest spatial areas that can be derived from the publicly available versions of the NRI. The results show that a total shift into conventional tillage results in a nearly universal loss of carbon relative to the baseline; in contrast, a total shift into no-till results in positive soil carbon gains for virtually the entire state as compared to the baseline. The only exceptions are a few small polygons for both scenarios. (It is not clear why these polygons did not follow the overall predicted trends). The results shown in Figures 4 and 5 are consistent with general expectations that no-till would provide enhanced soil carbon benefits over other tillage options for most conditions.

Application by the Natural Resources Conservation Service

The NRCS-RAD has incorporated i_EPIC into a modeling system they have developed to perform assessments of different cropping systems and management practices for agricultural areas across the 48 contiguous U.S. states. The NRI is again a key database for this system, providing soil type, cropping system, and other data required to perform the simulations. The initial application of the system involved executing nearly one million EPIC0250 simulations for an array of fertilizer, tillage, and monoculture cropping system treatments, in combination with different soil and climate conditions. Soil and climate "clusters" have been created for the system, in which statistically similar soils and climates are clustered together and ultimately are represented by a single soil or climate for the actual analysis (thus greatly reducing the number of required simulations). The processing of the climate data transcended state boundaries and resulted in 66 contiguous climate areas, as shown in Figure 6. The soil clustering process was based on the soil types identified for each NRI point and was performed on a state-by-state basis; exact plotting of these clusters is difficult because they are not always contiguous. In total, 7,309 unique soil-climate cluster combinations have been developed for the NRCS

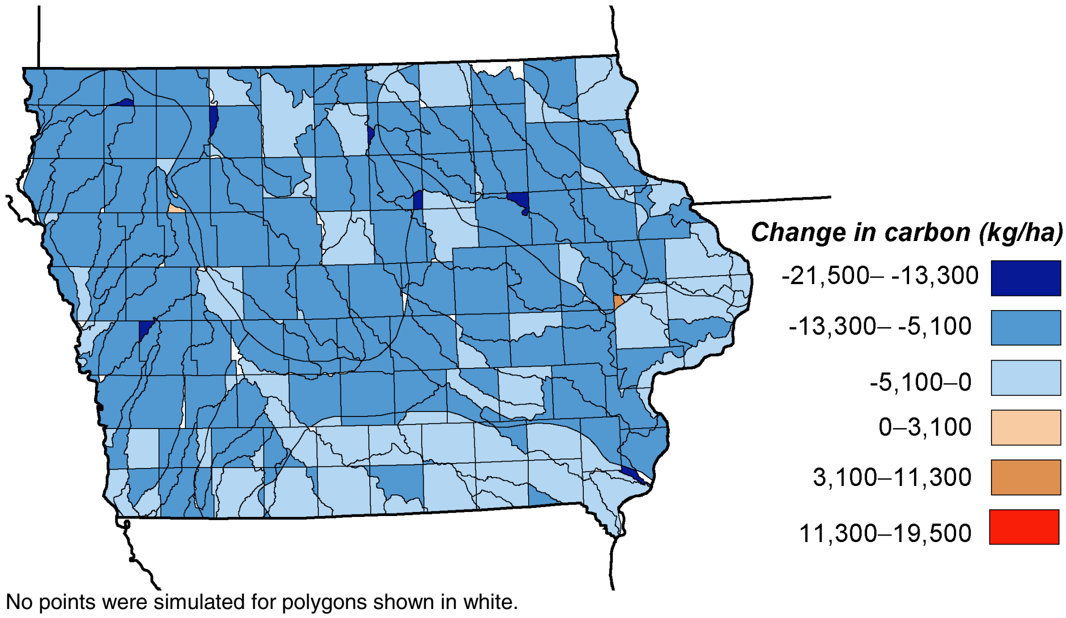


FIGURE 4. The change in soil carbon by National Resources Inventory polygon for the EPIC1015 conventional tillage scenario as compared to the baseline set of simulations

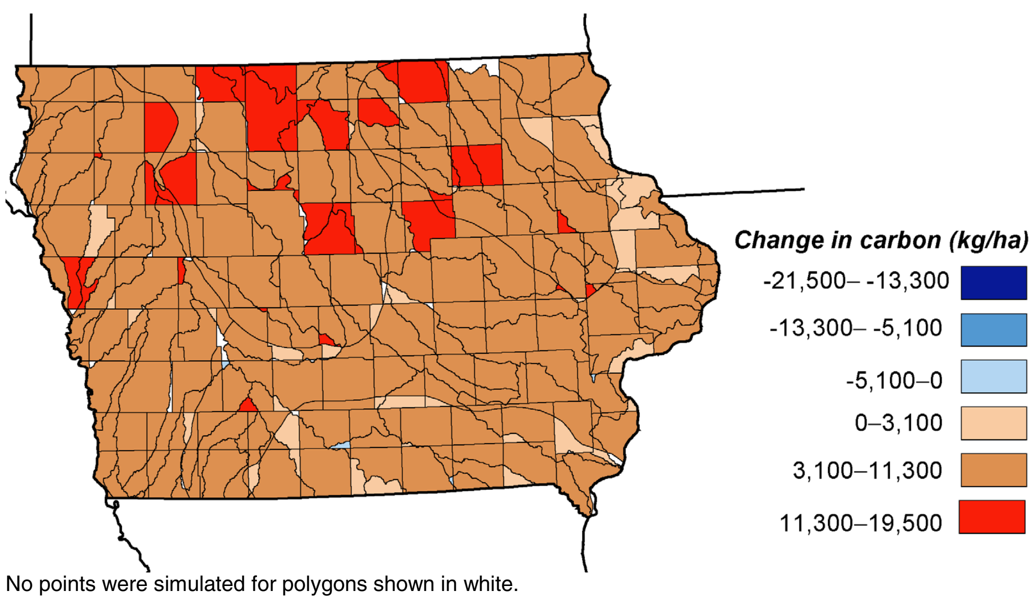


FIGURE 5. The change in soil carbon by National Resources Inventory polygon for the EPIC1015 no-till scenario as compared to the baseline set of simulations

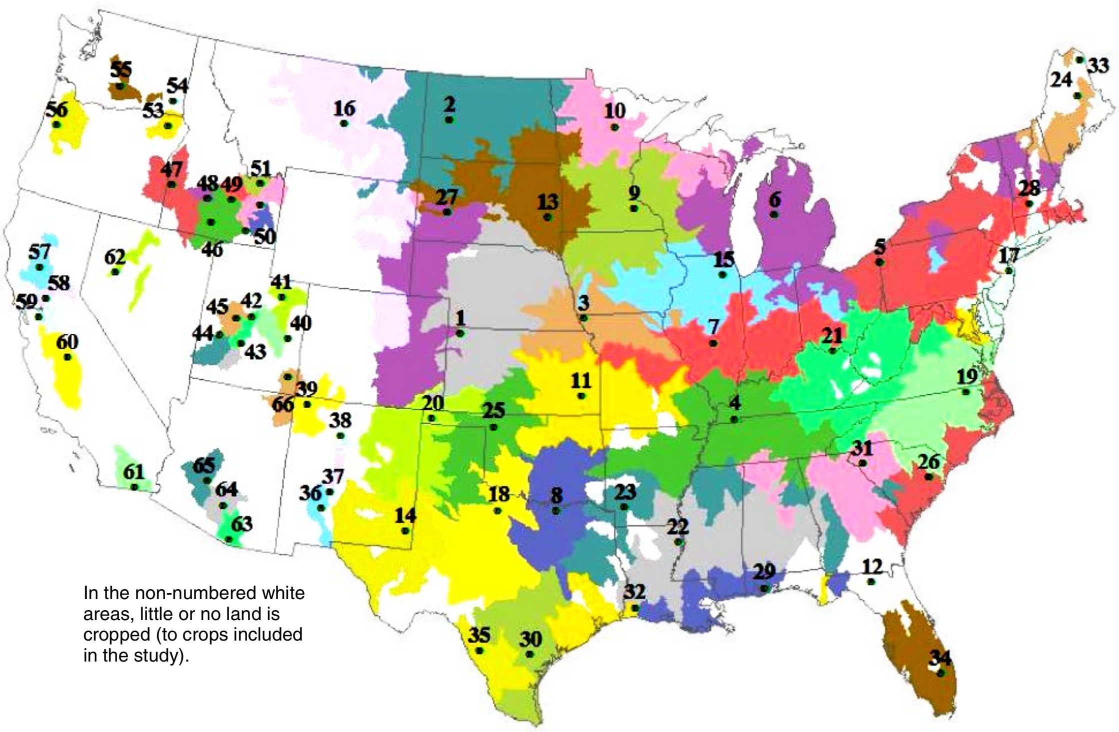


FIGURE 6. The 66 climate clusters developed for the National Resources Conservation Service modeling system

modeling system. However, the total number of homogeneous resource areas is about 35,000, when cropping systems and other factors are accounted for. Code has been developed to translate all of the required data needed for the EPIC simulations into the proper Access database format, so that the EPIC runs can be executed with i_EPIC.

An example output of the system is shown in Figure 7 for changes in estimated losses of labile Phosphorus (P) between 1992 and 1997, based on changes in the land use mix that occurred between the 1992 NRI and 1997 NRI. The results are aggregated to U.S. Geological Survey (USGS) eight-digit watersheds, one of the spatial units included in the NRI. The western areas shown in Figure 6 were not included in this analysis. A complete national assessment has been performed with the system, producing a suite of edge-of-field erosion and nutrient (N and P) indicators based on 40-year simulations[7] of all combinations of variables.

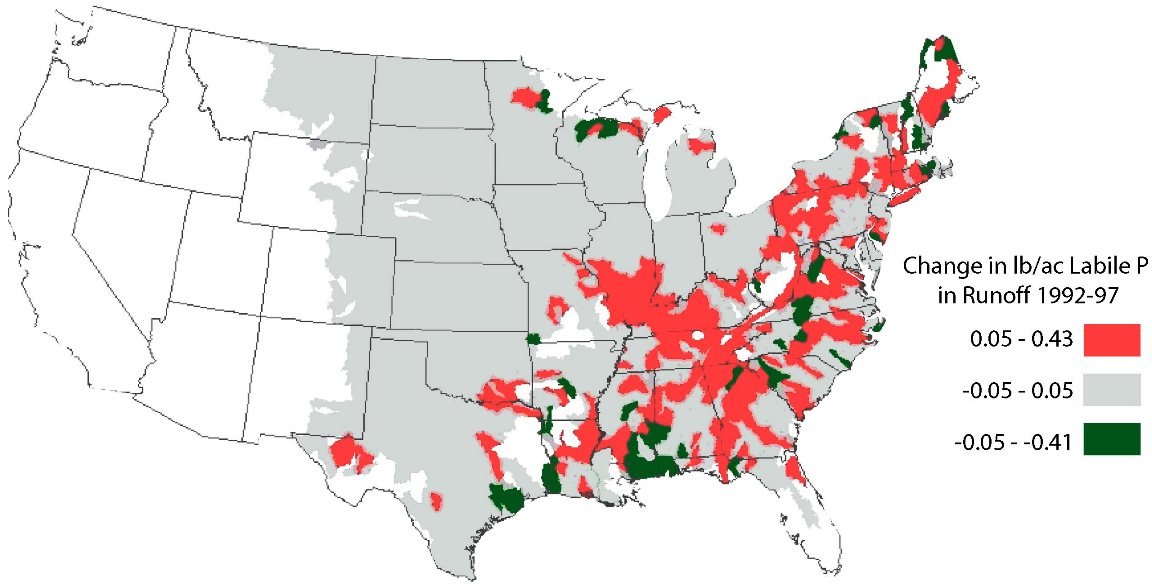
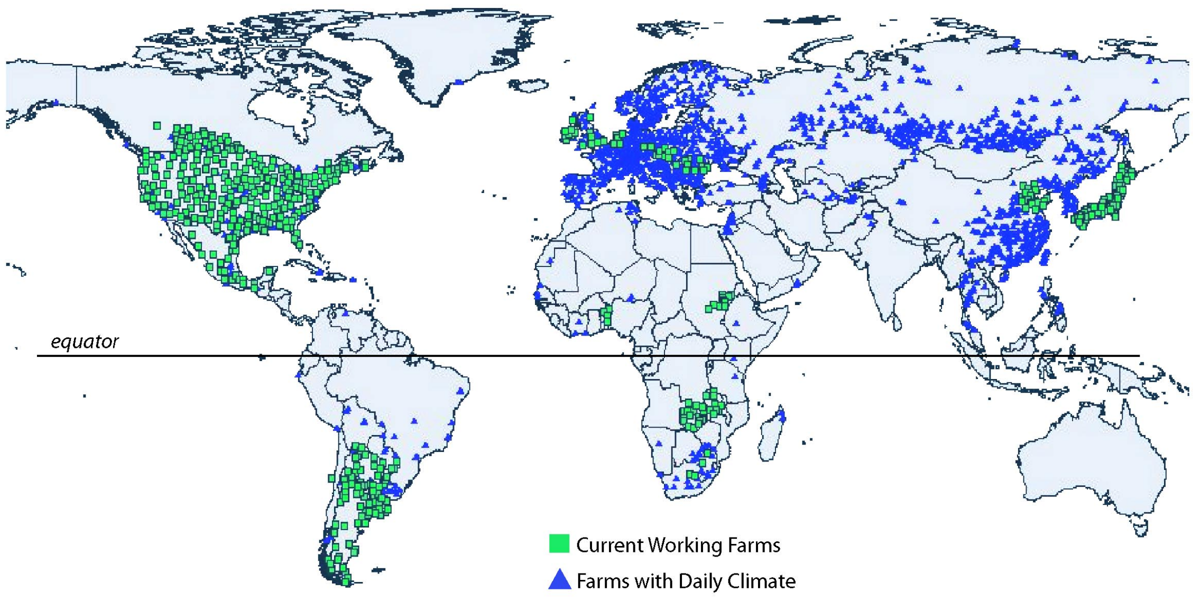


FIGURE 7. Change in labile P between 1992 and 1997 for cropped areas simulated by Natural Resources Conservation Service Resource Assessment Division researchers using EPIC0250 (western areas were not included in this analysis)

Development of the NRCS system is a continually evolving process. At present, the system is being configured to perform a national assessment with EPIC0250 of Comprehensive Nutrient Management Plans that the NRCS will be conducting for a significant portion of U.S. livestock operations. A key aspect of this study is that the environmental impacts of N and P in applied manure will also be accounted for. The NRCS-RAD researchers also are planning to perform other future analyses with EPIC1015.

Example from the Joint Global Change Research Institute

Researchers at the JGCRI are developing a set of representative farms (EPIC1015 simulations) that will allow analysis of variations in management, cropping systems, and climate conditions for major agricultural production regions across the globe. The initial step involves identifying sources of soil and climate information that contain the data required for EPIC1015. As shown in Figure 8, over 400 EPIC1015 representative farms have been constructed so far (green squares) and sufficient soil and climate data is available to allow the development of approximately 1,500 more farms (blue triangles).



Source: A.M. Thomson, Joint Global Change Research Institute

FIGURE 8. Location of Joint Global Change Research Intitute farm models (green squares) and potential models (blue triangles)

These EPIC1015 representative farms are intended to represent conditions typical of the regions in which they are located.

The data for each of these farms is being loaded into the proper Access format to allow the simulations to be performed with i_EPIC. To date, efforts have focused on simulating baseline climate and other conditions for different types of crops for the existing farm models. For example, preliminary results are shown in Figure 9 for 30-year average dryland wheat yields predicted with EPIC1015 for the more than 400 farm models. Development of the baseline scenarios for each farm has included contacting researchers in about 20 different countries to determine the best assumptions for tillage, fertilizer, and other management inputs. Validation studies of the baseline conditions with measured data have also been initiated for two areas in Argentina.

Future efforts will focus on performing a range of alternative climate, management, and or cropping system scenarios with the complete set of EPIC1015 representative farms. Modification of management and other inputs within the i_EPIC framework will allow rapid assessments of different scenarios.

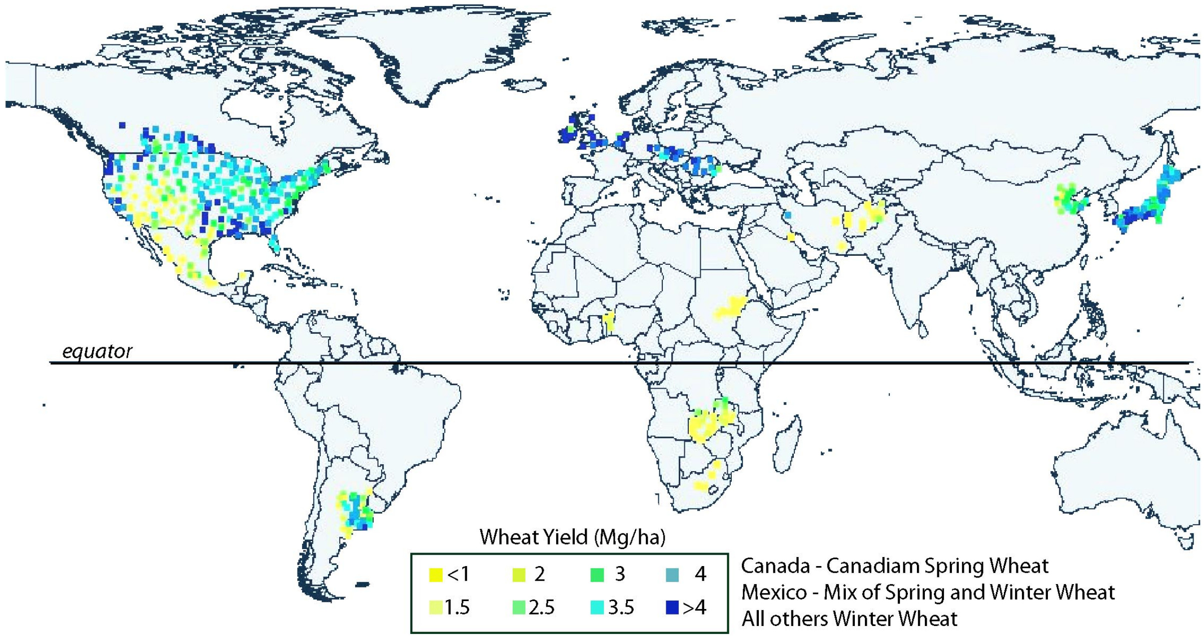


FIGURE 9. Dryland wheat yields estimated with the Joint Global Change Research Intitute EPIC1015 farm models for baseline climate, soil, and management conditions

Conclusions

The i_EPIC software package has proven to be a robust tool for managing large sets of EPIC simulations for regional analyses of soil carbon changes, nutrient and erosion losses, and other environmental indicators in response to variations in management practices, cropping systems, climate inputs, and soil types. The software can be freely downloaded by anyone who has Internet access. The i_EPIC system and supporting online documentation is expected to continue to evolve, which should facilitate even easier use of the software in the future. We expect that EPIC1015 will be released for general public use in the near future. This EPIC version will allow enhanced applications of the model for those users who are interested in incorporating improved soil carbon sequestration impacts within their regional assessments.

Endnotes

1. The first digit in 1015 represents the last digit of the year that the version was released (i.e., 2001) while the last three digits represent the julian date of the release (i.e., day 15).

2. Both i_Century and i_SWAT can be downloaded and used as desired; however, these two software packages were developed after i_EPIC and thus are less reliable.

3. We recommend that users work only with the version of i_EPIC that works with Access 2000 because the Access 97 version has not been updated in more than two years.

4. The land use mix is based on either the 1992 or 1997 NRI; a link to the 1992 NRI is needed when using the 1997 NRI to access tillage and tile drainage data that are not included in the 1997 NRI.

5. The economic model essentially assumes that each NRI point is a farm.

6. Century would be applied the same way; NRI points with similar soils and other features are clustered together for SWAT.

7. The output for years 1 through 10 are assumed to be a “pre-equilibrium status” and are not included in the final analysis.

References

Apezteguía, H.P., R.C. Izaurralde, and R. Sereno. 2002. "Simulation of Soil Organic Matter Dynamics as Affected by Land Use and Agricultural Practices in Semiarid Córdoba." Agronomy Abstracts, CD-ROM. American Society of Agronomy, Madison, WI.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. "Large Area Hydrologic Modeling and Assessment." Part I: Model Development. *J. Amer. Water Resour. Assoc.* 34(1): 73-89.

Babcock, B.A., J. Wu, T. Campbell, P.W. Gassman, P.D. Mitchell, T. Otake, M. Siemers, and T.M. Hurley. 1998. *RAPS 1997: Agriculture and Environmental Outlook*. Ames, IA: Center for Agricultural and Rural Development, Iowa State University.

Bernardos, J.N., E.F. Viglizzo, V. Jouvet, F.A. Lértora, A.J. Pordomingo, and F.D. Cid. 2001. "The Use of EPIC Model to Study the Agroecological Change During 93 Years of Farming Transformation in the Argentine Pampas." *Agric. Syst.* 69:215-34

Brown, R.A., and N.J. Rosenberg. 1999. "Climate Change Impacts on the Potential Productivity of Corn and Winter Wheat in Their Primary United States Growing Regions." *Climate Change* 41: 73-107.

Chung, S.W., P.W. Gassman, L.A. Kramer, J.R. Williams, and R. Gu. 1999. "Validation of EPIC for Two Watersheds in Southwest Iowa." *J. Environ. Qual.* 28(3): 971-79.

Chung, S.W., P.W. Gassman, D.R. Huggins, and G.W. Randall. 2001. "EPIC Tile Flow and Nitrate Loss Predictions for Three Minnesota Cropping Systems." *J. Environ. Qual.* 30(3): 822-30.

Edwards, D.R., V.W. Benson, J.R. Williams, T.C. Daniel, J. Lemunyon, and R.G. Gilbert. 1994. "Use of the EPIC Model to Predict Runoff Transport of Surface-Applied Inorganic Fertilizer and Poultry Manure Constituents." *Trans. ASAE* 37(2): 403-9.

Favis-Mortlock, D.T., R. Evans, J. Boardman, and T.M. Harris. 1991. "Climate Change, Winter Wheat Yield and Soil Erosion on the English South Downs." *Agric. Syst*. 37: 415-33.

Gassman, P.W., J. Wu, P.D. Mitchell, B.A. Babcock, T.M. Hurley, and S.W. Chung. 1998. "Impact of U.S. Agricultural Policy on Regional Nitrogen Losses." In *Proceedings of the 3rd International Conference on Diffuse Pollution* (Poster Papers), 31 Aug.-4 Sept., Edinburgh, Scotland. International Association of Water Quality, London, UK, pp. 115-22.

Izaurralde, R.C., P.W. Gassman, A. Bouzaher, J. Tajek, P.G. Lakshminarayan, J. Dumanski, and J.R. Kiniry. 1997. "Application of EPIC within an Integrated Modelling System to Evaluate Soil Erosion in the Canadian Prairies." In *Modern Agriculture and the Environment*. Edited by D. Rosen, E. Tel-Or, Y. Hadar, and Y. Chen. Dordrect, Netherlands: Kluwer Academic Publishers, pp. 269-285.

Izaurralde, R.C., J.R. Williams, W.B. McGill, and N.J. Rosenberg. 2001. "Simulating Soil Carbon Dynamics, Erosion, and Tillage with EPIC." Presented at the First National Conference on Carbon Sequestration, sponsored by the U.S. Department of Energy – National Energy Technology Laboratory, 14-17 May, Washington, D.C.

Izaurralde, R.C., J.R. Williams, W.B. McGill, N.J. Rosenberg, and M.C. Quiroga Jakas. 2002. "Simulating Soil C Dynamics with EPIC: Model Description and Testing Against Long-Term Data." Agronomy Abstracts, CD-ROM. American Society of Agronomy, Madison, WI.

Lakshminarayan, P.G., P.W. Gassman, A. Bouzaher, and R.C. Izaurralde. 1996. "A Metamodeling Approach to Evaluate Agricultural Policy Impact on Soil Degradation in Western Canada." *Can. J. Agric. Econ*. 44(3): 277-94.

Lee, J.L., D.L. Phillips, and R.F. Dodson. 1996. "Sensitivity of the US Corn Belt to Climate Change and Elevated CO_2." Part II: Soil Erosion and Organic Carbon. *Agric. Syst*. 52: 503-21.

Mitchell, G., R.H. Griggs, V. Benson, and J. Williams. 1996. "EPIC User's Guide (draft) version 5300: The EPIC Model Environmental Policy Integrated Climate (Formerly Erosion Productivity Impact Calculator)." Texas Agricultural Experiment Station, Blackland Research Center, Temple, TX.

Nusser, S.M., and J.J. Goebel. 1997. "The National Resources Inventory: A Long-Term Multi-Resource Monitoring Programme." *Environ. and Ecolog. Stat.* 4: 181-204.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel. 1994. "A General Model for Soil Organic Matter Dynamics: Sensitivity to Litter Chemistry, Texture and Management." *Quantitative Modeling of Soil Forming Processes*. SSSA Special Publication 39. Soil Science Society of America, Madison, WI.

Phillips, D.L., P.D. Hardin, V.W. Benson, and J.V. Baglio. 1993. "Nonpoint Source Pollution Impacts of Alternative Agricultural Management Practices in Illinois: A Simulation Study." *J. Soil and Water Conser*. 48(5): 449-57.

Potter, K.N., J.R. Williams, F.J. Larney, and M.S. Bullock. 1998. "Evaluation of EPIC's Wind Erosion Submodel using Data from Southern Alberta." *Can. J. Soil Sci.* 78: 485-92.

Stockle, C.O., P.T. Dyke, J.R. Williams, C.A. Jones, and N.J. Rosenberg. 1992. "A Method for Estimating the Direct and Climatic Effects of Rising Atmospheric Carbon Dioxide on Growth and Yield of Crops." Part II: Sensitivity Analysis at Three Sites in the Midwestern USA. *Agric. Syst*. 38: 239-56.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA, NRCS). n.d. National Resources Inventory. http://www.nrcs.usda.gov/technical/NRI (accessed April 7, 2003). Washington, D.C.

Williams, J.R. 1990. "The Erosion Productivity Impact Calculator (EPIC) Model: A Case History." *Phil. Trans. R. Soc. Lond*. 329: 421-28.

———. 1995. "The EPIC Model." In *Computer Models of Watershed Hydrology*. Edited by V.P. Singh. Highlands Ranch, CO: Water Resources Publications.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. "A Modeling Approach to Determining the Relationship between Erosion and Soil Productivity." *Trans. ASAE* 27(1): 129-44.

Williams, J.R., C.W. Richardson, and R.H. Griggs. 1992. "The Weather Factor: Incorporating Weather Variance into Computer Simulation." *Weed Technol*. 6: 731-35.

Wu, J., and B.A. Babcock. 1999. "Metamodeling Potential Nitrate Water Pollution in the Central United States." *J. Environ. Qual*. 28(6): 1916-28.