Historical Development and Applications of the EPIC and APEX Models

Philip W. Gassman, Jimmy R. Williams, Verel W. Benson,
R. César Izaurralde, Larry M. Hauck, C. Allan Jones, Jay D. Atwood,
James R. Kiniry, and Joan D. Flowers

Working Paper 05-WP 397
June 2005

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

Authors information: Philip W. Gassman, Center for Agricultural and Rural Development, Iowa State University; Jimmy R. Williams, Blackland Research and Extension Center, Texas A&M University; Verel W. Benson, Food and Agricultural Policy Research Institute, University of Missouri-Columbia; R. César Izaurralde, Joint Global Change Research Institute, University of Maryland; Larry M. Hauck, Texas Institute for Applied Environmental Research, Tarleton State University; C. Allan Jones, Texas Water Resources Institute, Texas A&M University, Jay D. Atwood, USDA-NRCS, Water Resources Assessment Team, Blackland Research and Extension Center, Texas A&M University; James R. Kiniry, USDA-ARS, Grassland Research Center, Texas A&M University; Joan D. Flowers, Carter & Burgess, Fort Worth, Texas.

This paper was presented at the 2004 ASAE/CSAE annual international meeting in Ottawa, Ontario, Canada, as Meeting Paper No. 042097.

This paper is available online on the CARD Web site: *www.card.iastate.edu*. Permission is granted to reproduce this information with appropriate attribution to the authors.

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

The development of the field-scale Erosion Productivity Impact Calculator (EPIC) model was initiated in 1981 to support assessments of soil erosion impacts on soil productivity for soil, climate, and cropping conditions representative of a broad spectrum of U.S. agricultural production regions. The first major application of EPIC was a national analysis performed in support of the 1985 Resources Conservation Act (RCA) assessment. The model has continuously evolved since that time and has been applied for a wide range of field, regional, and national studies both in the U.S. and in other countries. The range of EPIC applications has also expanded greatly over that time, including studies of (1) surface runoff and leaching estimates of nitrogen and phosphorus losses from fertilizer and manure applications, (2) leaching and runoff from simulated pesticide applications, (3) soil erosion losses from wind erosion, (4) climate change impacts on crop yield and erosion, and (5) soil carbon sequestration assessments. The EPIC acronym now stands for Erosion Policy Impact Climate, to reflect the greater diversity of problems to which the model is currently applied. The Agricultural Policy EXtender (APEX) model is essentially a multi-field version of EPIC that was developed in the late 1990s to address environmental problems associated with livestock and other agricultural production systems on a whole-farm or small watershed basis. The APEX model also continues to evolve and to be utilized for a wide variety of environmental assessments. The historical development for both models will be presented, as well as example applications on several different scales.

Keywords: APEX, carbon sequestration, climate change, EPIC, modeling, soil erosion, water quality.

HISTORICAL DEVELOPMENT AND APPLICATIONS OF THE EPIC AND APEX MODELS

Introduction

The 1977 Resources Conservation Act (RCA) charged the U.S. Department of Agriculture (USDA) with the responsibility to assess the status of the nation's soil and water resources on a regular basis. The first RCA appraisal conducted in 1980 revealed a significant need for improved technology for evaluating the impacts of soil erosion on soil productivity (Putnam, Williams, and Sawyer 1988). In response, the Erosion Productivity Impact Calculator (EPIC) model was developed by a USDA modeling team in the early 1980s to address this technology gap (Williams, Jones, and Dyke 1984; Williams 1990; Sharpley and Williams 1990; Jones et al. 1991). The first major application of EPIC was for the second RCA appraisal in 1985, in which the model was used to evaluate soil erosion impacts for 135 U.S. land resource regions (Putnam, Williams, and Sawyer 1988). Ongoing evolution of the model, including incorporation of additional functions related to water quality and atmospheric CO_2 change, resulted in the model name eventually being changed to Environmental Policy Impact Climate (Williams et al. 1996). The latest version of EPIC features enhanced carbon cycling routines (Izaurralde et al. 2001) that are based on the approach used in the Century model (Parton et al. 1994).

Numerous applications of EPIC have been performed in the United States and in other regions of the world across a broad spectrum of environmental conditions. Example applications include assessment of sediment and nutrient losses as a function of different tillage systems, crop rotations, and fertilizer rates (Phillips et al. 1993; King, Richardson, and Williams 1996); nutrient losses from livestock manure applications (Edwards et al. 1994; Pierson et al. 2001); nitrate-nitrogen (NO_3-N) losses through subsurface tile drainage (Chung et al. 2001; Chung et al. 2002); nutrient cycling as a function of cropping system (Cavero et al. 1999; Bernardos et al. 2001); soil loss due to wind erosion (Potter et al. 1998; Bernardos et al. 2001); climate change impacts on crop yield and/or soil erosion (Favis-

Mortlock et al. 1991; Brown and Rosenberg 1999); losses from field applications of pesticides (Williams, Richardson, and Griggs 1992; Sabbagh et al. 1992); irrigation impacts on crop yields (Cabelguenne, Jones, and Williams 1995; Rinaldi 2001); estimation of soil temperature (Potter and Williams 1994; Roloff, de Jong, and Nolin 1998a); and soil carbon sequestration as a function of cropping and management systems (Lee, Phillips, and Liu 1993; Apezteguía, Izaurralde, and Sereno 2002). The flexibility of EPIC has also led to its adoption within several integrated economic and environmental modeling systems that have been used to evaluate agricultural policies at the farm, watershed, and/or regional scale (e.g., Taylor, Adams, and Miller 1992; Bernardo et al. 1993; Foltz, Lee, and Martin 1993; Babcock et al. 1997).

The Agricultural Policy EXtender (APEX) model (Williams et al. 1995; Williams 2002) was developed in the 1990s to facilitate multiple subarea scenarios and/or manure management strategies, such as automatic land application of liquid manure from waste storage ponds, which cannot be simulated in EPIC. The catalyst for creating APEX was the U.S. Environmental Protection Agency (USEPA) funded "Livestock and the Environment: A National Pilot Project (NPP)," which was initiated in 1992 to study livestock environmental problems on a watershed basis. The APEX model was used extensively for a wide range of livestock farm and nutrient management (manure and fertilizer) scenarios within the Comprehensive Economic Environmental Optimization Tool – Livestock and Poultry (CEEOT-LP), an economic-environmental modeling system developed for the NPP (Gassman et al. 2002; Osei et al. 2000; Osei, Gassman, and Saleh 2000; Osei et al. 2003a, b). It has also been applied within a number of other studies.

A brief overview of the structure of both models is presented here, followed by reviews of how the models have been applied up to the present time. Emerging applications of the two models are also discussed.

Overview of EPIC

The EPIC model can be subdivided into nine separate components defined as weather, hydrology, erosion, nutrients, soil temperature, plant growth, plant environment control, tillage, and economic budgets (Williams 1990). It is a field-scale model that is designed to simulate drainage areas 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 for hundreds and even thousands of years. A wide range of crop rotations and other vegetative systems can be simulated with the generic crop growth routine used in EPIC. An extensive array of tillage systems and other management practices can also be simulated with the model. Seven options are provided for simulating water erosion and five options are available for simulating potential evapotranspiration (PET). Detailed discussions of the EPIC components and functions are given in Williams, Jones, and Dyke 1984; Williams 1990; Sharply and Williams 1990; and Williams 1995.

EPIC Applications

Initial tests of the EPIC model were reported by Williams, Renard, and Dyke (1983), which were performed in support of the 1985 RCA analysis. The model was shown to replicate realistically mean surface runoff and sediment yields that were measured for three small watersheds in Falls County, Texas, and for corn, oat, or soybean yields that were measured in Iowa, Missouri, and Ohio. Nearly 12,000 100-year EPIC simulations were then performed for different crop, tillage, soil, climate, and conservation practice combinations to support the RCA analysis, which included economic assessments conducted with a linear programming model (Putnam, Williams, and Sawyer 1988).

The EPIC model has continued to evolve and to be applied to an ever-increasing range of scenarios since the 1985 RCA analysis. Some applications have focused specifically on testing of different EPIC components, which in some cases resulted in modifications to existing routines and improved model performance. Other enhancements and refinements have been made to the model to facilitate the interest of various users or to meet the needs of specific applications. Table 1 lists examples of modifications that have been made to the EPIC model over roughly the past 15 years. “Spin-off” versions of the model have also been developed by several users for region- or task-specific applications, for example, the AUSCANE model created by Jones et al. (1989) to simulate Australian sugarcane production. Trends in the use of EPIC are highlighted here as a function of example applications for key EPIC indicators such as estimation of crop yields and soil erosion losses by wind and water. Subcategories are also delineated for notable region- or application-specific uses.

TABLE 1. Examples of modifications to EPIC components or input data since the second RCA study

Modified Component or Input Data	Source[a]
Improved and expanded crop growth submodel	Williams et al. (1989)
Enhanced root growth functions	Jones et al. (1991)
Improved nitrogen fixation routine for legume crops that calculates fixation as a function of soil water, soil N, and crop physiological stage	Bouniols et al. (1991)
Incorporation of pesticide routines from GLEAMS model	Sabbagh et al. (1991)
Improved crop growth parameters for sunflower	Kiniry et al. (1992a)
Incorporation of CO_2 and vapor pressure effects on radiation use efficiency, leaf resistance, and transpiration of crops	Stockle et al. (1992a)
Incorporation of functions that allow two or more crops to be grown simultaneously	Kiniry et al. (1992b)
Improved soil temperature component	Potter and Williams (1994)
Improved crop growth parameters for cereal, oilseed, and forage crops grown in the North American northern Great Plains region	Kiniry et al. (1995)
Improved and expanded weather generator component	Williams (1995)
Incorporation of NRCS TR-55 peak runoff rate component	Williams (1995)
Incorporation of MUSS, MUST, and MUSI water erosion routines	Williams (1995)
Incorporation of nitrification-volatilization component	Williams (1995)
Improved water table dynamics routine	Williams (1995)
Incorporation of RUSLE water erosion equation	Renard (1997)
Improved snowmelt runoff and erosion component	Purveen et al. (1997)
Improved EPIC wind erosion model (WESS)	Potter et al. (1998)
Incorporation of Baier-Robertson PET routine	Roloff et al. (1998)
Incorporation of Green and Ampt infiltration function	Williams, Arnold, and Srinivasan (2000)
Enhanced carbon cycling routine that is based on the Century model approach	Izaurralde et al. (2004)
Incorporation of a potassium (K) cycling routine	De Barros, Williams, and Gaiser (2004)

[a]Some sources do not explicitly document the modification but are the best description of the modification available or present an application of the specific subcomponent.

Crop Growth and Yield Studies

A key output provided by EPIC is crop yield predictions. Several studies have been performed in the United States and other countries that focused specifically on testing the accuracy of EPIC crop growth and yield predictions. Such tests have also been incorporated as parts of other studies. One of the most comprehensive tests of the crop growth submodel was performed by Williams et al. (1989), who describe the results of testing an updated EPIC crop growth model (Table 1) for simulated barley, corn, rice, soybean, sunflower, and wheat yields at several U.S. locations and for sites in Asia, France, and South America. The predicted yields were compared with measured yields for periods ranging from 1 to 11 years. The average predicted yields were always within 7% of the average measured yields, and there was no significant difference between any of the simulated and measured yields at the 95% confidence level. However, r^2 statistics computed between the simulated and measured yields of the six crops ranged from relatively strong values of 0.80 and 0.65 for wheat and corn to only 0.20 for barley and soybean.

EPIC-predicted yields have been shown in other studies to replicate accurately both mean and annual yields for different crops and conditions. Bryant et al. (1992) found that EPIC accurately predicted mean and annual corn yields measured for 38 irrigation stress experiments conducted during the 1975-77 period at Bushland, Texas, after the effects of a hail storm were accounted for in 1976. Gray et al. (1997) reported r^2 values of 0.82 and 0.85 for corn yield production functions developed from EPIC simulations that were performed for irrigation timing experiments conducted at Bushland, Texas, during the years 1990-93. Geleta et al. (1994) found that predicted mean and annual yields accurately reflected irrigated corn, sorghum, and winter wheat yields measured near Goodwell in the Oklahoma Panhandle region between 1984 and 1988 using a version of EPIC called EPIC-PST (Sabbagh et al. 1991). Parsons, Pease, and Martens (1995) reported that EPIC predicted mean yields accurately and explained 55% to 89% of the measured yield variance for five of six treatments (excluding 1986 from four of the treatments) for corn grown during the 1978-93 period on three Virginia soil types fertilized with either inorganic fertilizer or a “heavy” manure application. Cavero et al. (1997) and Cavero et al. (1999) found that EPIC replicated measured annual yields accurately, except when disease problems affected yields, for irrigated tomato, safflower, and winter wheat grown

during the 1994-95 period for conditions representative of the Sacramento Valley in California. Roloff, de Jong, and Nolin (1998a) found that EPIC adequately simulated mean and annual soybean yields for two sites located at Barrhaven, Ontario, and St. Antoine, Quebec, but corn yields estimated by EPIC were less accurate. Mean and annual corn, soybean, and alfalfa yields estimated by EPIC generally reflected corresponding yields measured within continuous corn, corn-soybean, and continuous alfalfa rotations during the 1990-93 period near Lamberton, Minnesota, although errors of 25%-50% occurred for 4 of the 12 annual predicted yields (Chung et al. 2001). Perez-Quezada et al. (2003) found that EPIC replicated yield variability measured for wheat, tomatoes, beans, and sunflowers grown in a commercial field in the Sacramento Valley, California, but the model was weaker at reproducing yields measured at specific points in the field.

Other studies have shown that EPIC was able to replicate measured mean or median yields but not observed interannual yield variability. Examples include (1) predicted yields from 144 EPIC simulations for soybeans grown in 40 fields in 1982 and/or 1983 in fields near Watkinsville, Georgia (Martin, Nearing, and Bruce 1993); (2) predicted spring wheat yields in long-term continuous wheat, fallow-wheat, or fallow-wheat-wheat rotations grown over 30, 79, 15, and 27 years at Melfort, Saskatchewan (Moulin and Beckie 1993), Lethbridge, Alberta (Touré, Major, and Lindwall 1994), Swift Current, Saskatchewan (Kiniry et al. 1995), and Swift Current, Saskatchewan (Roloff et al. 1998), respectively; and (3) predicted corn yields in continuous corn grown during the 1976-87 period at Treynor, Iowa (Chung et al. 1999). Bernardos et al. (2001) found that long-term yield trends predicted by EPIC over several decades for the Argentine Pampa region were more accurate than the estimated yield variation, based on comparisons with historical yield data for corn, wheat, and sunflower. Warner et al. (1997a) report that annual yields estimated by EPIC did not correlate well with the measured yields and that the model exhibited a bias toward overprediction of yields for corn grown over a total of 15 treatment years (five nitrogen fertilizer rates for three years each) at Storrs, Connecticut. However, some studies noted that EPIC tended to underestimate peak yields and overestimate low yields (Bryant et al. 1992; Touré, Major, and Lindwall 1994). Martin, Nearing, and Bruce (1993) further noted that differences in the predicted EPIC yields between erosion classes

were less those measured. Chung et al. (2002) also found that EPIC lacked sensitivity to tillage effects on yields.

Moulin and Beckie (1993) and Kiniry et al. (1995) concluded that EPIC could be a valuable tool for simulating yields and environmental impacts for long-term studies representative of Canadian Prairie conditions. Roloff et al. (1998) reached the same conclusion, provided the Baier-Robertson PET routine was used. Touré, Major, and Lindwall (1994) suggested that EPIC had the best potential for analyzing climate change impacts on agricultural production out of five models evaluated. Parsons, Pease, and Martens (1995) concluded that EPIC could be used to assess the effects of different nutrient treatments, including very high manure rate applications, on crop yield. Martin, Nearing, and Bruce (1993) concluded that EPIC could be useful for performing relative comparisons between different erosion class soils. Bryant et al. (1992) pointed out that EPIC (and other simulation models) are best used to generate simulated yield distributions that are similar to measured yield distributions, rather than trying to match measured yields in each single year. Similar conclusions can be drawn from the majority of the other studies reviewed here. However, adjustments to standard EPIC input parameters or to EPIC functions are sometimes necessary to achieve acceptable yield predictions, such as the adjustment made by Steiner, Williams, and Jones (1987) to the EPIC dry matter production conversion factor to facilitate more accurate simulation of winter wheat and sorghum yields during the 1958-84 period in a dryland wheat-sorghum-fallow rotation at Bushland, Texas.

Yield Simulation Studies in Southern France

A more aggressive adaptation of EPIC was carried out in southern France as part of an extensive research effort by researchers at the National Institute of Research in Agronomy (INRA) Station at Toulouse-Auzeville. Cabelguenne et al. (1990) found that the standard EPIC model adequately replicated measured mean yields of corn, grain sorghum, sunflower, and soybean (but not winter wheat) that were grown in complex rotations with varying levels of management and concluded that the model could be used for simulating a range of irrigated summer crop scenarios for southern France. However, concurrent research by Quinones and Cabelguenne (1990) revealed that EPIC could not adequately simulate some conditions of severe water stress. To address this weakness, the

latter authors incorporated a module that accounted for three corn phenological stages (vegetative, flowering, and grain filling), different levels of drought sensitivity impacts during each stage, including effects on the harvest index, and variation in water extraction by corn as a function of layer depth. Simulation results obtained with this modified version of EPIC for six irrigation strategies were consistent with reported effects of drought stress during critical periods of grain yield development and indicated that the modified model could produce more accurate results for southern France irrigation studies (Cabelguenne, Jones, and Williams 1995). Similar results were reported for evaluation of wheat irrigation strategies with the "EPICPHASE wheat simulation model" (Debaeke 1995), another modified version of EPIC designed to more accurately simulate water stress impacts on wheat growth and yields. Further applications and development focused on a modified version of EPIC referred to as EPICPhase, which included real-time corn irrigation simulations (Cabelguenne et al. 1997), expanded water extraction and stress simulation capabilities for corn, sunflower, soybean, sorghum, and wheat (Cabelguenne and Debaeke 1998), and a yield validation study of the same five crops (Cabelguenne, Debaeke, and Bouniols 1999). (EPICphase, EPICPHASE, and EPIC-PHASE are versions of the name used for the modified EPIC in published literature.) The final version of EPICphase includes other modifications performed by the Toulouse INRA Agronomy Station such as improved crop parameters (Table 1) and modified functions for sunflowers (Kiniry et al. 1992b; Texier, Blanchet, and Bouniols 1992) and an improved nitrogen fixation routine for legume crops (Table 1) developed by Bouniols et al. (1991). It is notable that second-generation usage of EPICphase has occurred in Spain, where the model has been further modified, validated, and applied for irrigation scenarios (Cavero et al. 2000; Santos et al. 2000; Cavero et al. 2001).

Irrigation Studies

Crop yields generated by EPIC have served as a cornerstone of several studies focused on analyses of irrigation. Bryant et al. (1992) found that EPIC can be used to assess the impacts of different irrigation amounts and timings, based on validation of the model for the 38 different irrigation stress experiments at Bushland, Texas. Rinaldi (2001) used EPIC, following calibration by Ventrella and Rinaldi (1999) and others, to assess over 60 45-year scenarios of irrigation timing and amount strategies for sunflowers at Foggia in

southern Italy. The results showed that the "bud flower stage" was the most important period for irrigation, 250-300 mm of seasonal irrigation water equated to the highest water use efficiency value, and that the model is a useful tool for comparing multiple management strategies at the farm or regional scale. Tayfur et al. (1995) calibrated a "salinity extended EPIC model" with alfalfa yield and salinity data collected at the Fruita Research Center of Colorado and then used the modified EPIC to assess the effects of different summer water stress management practices on alfalfa yields and salinity movement in the Imperial Valley in California. They concluded that the modified model was a viable tool for simulating total alfalfa yield and average soil salinity for both optimal and stressed conditions, provided the stress period did not become overly prolonged. Geleta et al. (1994) used EPIC-PST to model corn, sorghum, and winter wheat yields within 20-year rotation scenarios on four soil types that were representative of the Oklahoma Panhandle for both dryland production (sorghum and wheat only) and for four irrigation management schemes: conventional furrow, improved furrow, center pivot sprinkler, and low-energy precision application (LEPA). The predicted sorghum and winter wheat yields were influenced by both soil type and irrigation system while the estimated corn yields were unaffected by irrigation system. Ellis et al. (1993) simulated nine different irrigation practices in EPIC for cotton production in the Trans-Pecos region of western Texas. The predicted yields were used in the FLIPSIM whole-farm simulation model to determine the best strategies for debt-ridden producers in the region to maintain financial viability during the 1987-91 production period. The analysis showed that water-intensive strategies would be the most profitable. A cost and benefit analysis was performed by Gray et al. (1997) for the Texas High Plains using EPIC and FLIPSIM. The results showed that no-till was economically more viable for all irrigation strategies assessed in the study.

Climate Change Effects on Crop Yields

The EPIC crop growth routine was modified by Stockle et al. (1992a) in order to account for the effects of elevated CO_2 on crop growth and yield (Table 1). The modifications consisted of incorporating functions that simulated the effects of changes in CO_2 concentrations and a vapor pressure deficit on crop radiation-use efficiency, leaf resistance, and transpiration. An initial assessment of potential climate change impacts on

crop yields with the CO_2 algorithms incorporated in EPIC was performed by Stockle et al. (1992b) for corn, wheat, and soybean cropping systems in the central United States. Yield increases were predicted for all crops in response to a CO_2 increase from 330 to 550 ppm, and mixed yield responses were predicted as a function of hypothetical increases or decreases in temperature or precipitation, with and without the increase in CO_2. The impact of an analog climate on crop production was analyzed by Easterling et al. (1992a) for the Missouri, Iowa, Nebraska, and Kansas (MINK) region using EPIC. They found that yields of grain crops, except wheat, would decline in response to the analog climate. Other MINK studies were also performed by Easterling et al. (1992c), Easterling et al. (1998), Easterling et al. (2001), and McKenney, Easterling, and Rosenberg (1992). Phillips, Lee, and Dodson (1996) reported variable crop yield impacts in response to 36 different hypothetical climate/CO_2 scenarios that were evaluated with EPIC for 100 USDA National Resource Inventory (NRI) points (http://www.nrcs.usda.gov/technical/land/nri01/) that were statistically representative of corn and soybean production in the U.S. Corn Belt. Touré, Major, and Lindwall (1995) used EPIC and three other models to evaluate the impacts of climate change on continuous dryland spring wheat grown at Lethbridge, Alberta, as a function of both hypothetical adjustments to temperature and precipitation inputs and climatic inputs derived from a global change model (GCM) scenario. Yield gains of 25% and 28% were projected for a warmer climate at current CO_2 levels (330 ppm) and a warmer climate with a doubling of CO_2, respectively.

A number of more recent studies have focused on driving EPIC with only GCM-derived climate data. Brown and Rosenberg (1999) assessed the impacts of future climate change from scenarios generated by three different GCMs on U.S. corn and wheat yields by simulating in EPIC 45 representative farms, which represented key wheat and corn production regions. Predicted impacts on yields ranged from -20% to +5% for corn and -76% to +18% for wheat. Izaurralde et al. (2003) analyzed the impacts of projected climate change from a single GCM for 2030 and 2095 on the productivity of four agricultural crops (corn, soybeans, alfalfa, and wheat) by simulating 204 representative farms in EPIC. Among other impacts, corn yields were predicted to increase in the Corn Belt and Great Lakes regions but to decrease in the Northern Plains in 2030, and national

wheat production was predicted to decline in both 2030 and 2095. Downscaled GCM weather output obtained through a regional climate model was used by Thomson, Brown, and Ghan (2002) to assess the impact of a doubling of CO_2 on dryland wheat yields in eastern Washington in EPIC. Average dryland wheat yields were predicted to increase by about 1 t/ha in response to the higher CO_2 levels. Tan and Shibasaki (2003) performed a global assessment of projected future climate change with EPIC. Their results show that global warming will be harmful to most crops. Other studies that have coupled GCM output with EPIC yield or soil water predictions include Brown and Rosenberg (1997), Brown et al. (2000), Dhakhwa et al. (1997), Dhakhwa and Campbell (1998), Easterling et al. (1992b) Easterling et al. (1992d), Easterling et al. (1996), Easterling et al. (1997), Huzár et al. (1999), Mearns et al. (1999), Mearns et al. (2001), Rosenberg et al. (1992), and Schneider, Easterling, and Mearns (2000).

Assessments of tropical Pacific El Niño, El Viejo, or La Niña Southern Oscillation (ENSO) phenomena effects on crop yields have also been assessed with EPIC in at least three other studies (Izaurralde et al. 1999; Adams et al. 2003; Legler, Bryant, and O'Brien 1999). Meza and Wilks (2004) have further investigated the effects of sea surface temperature anomalies (SSTA) on potato fertilization management in Chile with EPIC.

Nutrient Cycling and Nutrient Loss Studies

An extensive number of nutrient cycling and nutrient loss validation and scenario studies have been performed with EPIC (Tables 2 and 3). Several validation studies found that EPIC satisfactorily simulated measured soil nitrogen (N) and/or crop N uptake levels (Engelke and Fabrewitz 1991; Jackson et al. 1994; Beckie et al. 1995; Richter and Benbi 1996; Roloff, de Jong, and Nolin 1998b; Cavero et al. 1998; Cavero et al. 1999). However, less accurate soil N and crop N uptake results were reported in EPIC validation studies by Chung et al. (2001), Warner (1997a), and Warner et al. (1997b). Generally accurate predictions of leached N below the root zone or in tile flow, as compared with or implied by measured data, were found by Engelke and Fabrewitz (1991), Jackson et al. (1994), Richter and Benbi (1996), Cavero et al. (1997), Flowers, Easterling, and Hauck (1998), Cavero et al. (1999), and Chung et al. (2002). Somewhat weaker leached N or tile flow N loss predictions were found by Chung et al. (1999) and Chung et al. (2001), although both studies showed that EPIC was sensitive to long-term cropping and tillage

TABLE 2. Example nutrient cycling and/or nutrient loss validation studies

Region/Location	Description/Indicators Assessed	Source
Univ. of Georgia, Athens, Georgia	Dissolved reactive P in runoff from applied broiler litter to 6 grassland paddocks (0.72-0.79 ha); 3 years (1995-98)	Pierson et al. (2001)
Northwestern Arkansas	Sediment; organic N; N and P in runoff; total P; poultry manure applied to 4 pastures (20 months)	Edwards et al. (1994)
Near Treynor in southwest Iowa	Hydrologic balance, crop yield, and sediment; N leached and in runoff from fert.; 34 and 43 ha watersheds cropped in cont. corn; 12 years (1976-87)	Chung et al. (1999)
Muamee and Sandusky watersheds, mainly in Ohio	Sediment; N and P in runoff, organic N and P; fertilizer and manure applications; total area: 2.06x106 ha; 50 years	Forster et al. (2000)
Salinas Valley, Monterey County, California	Crop yield; N in soil, leached, and taken up by crop; crisphead lettuce; 11 ha field; 1990	Jackson et al. (1994)
Storrs, Connecticut	Crop yield; N in soil and taken up by crop; cont. corn (15 treatment years); 1987-1990	Warner et al. (1997a,b)
Sacramento Valley, California	Crop yield; N in soil, leached, and taken up by crop; tomato, wheat, and safflower rotations; 1994-95	Cavero et al. (1997; 1999)
Lamberton, Minnesota	Crop yield; tile flow; N in soil, in tile flow, and taken up by crop; cont. corn, corn-soybean, cont. alfalfa; 1990-93	Chung et al. (2001)
Nashua, Iowa	Crop yield; tile flow; N in tile flow; cont. corn, corn-soybean; 3 tillage levels; 0.4 ha plots; 1990-93	Chung et al. (2002)
Six field sites in Denmark, Belgium, the Netherlands, and the UK	Crop yields; N leached, mineralized, immobilized, denitrified, and/or in plant uptake; 1987-89 (1980-85 in the Netherlands)	Engelke and Fabrewitz (1991); Richter and Benbi (1996)
Two fields in Arroyo in the Colorado Watershed, Cameron County, Texas	Sediment; organic N and P; N and P in runoff; Total N and P in runoff and sediment; N in tile flow; sorghum-cotton rotation; 12 ha plots; 1 year	Flowers, Easterline, and Hauck (1998)

impacts on N losses. A sensitivity analysis by Benson et al. (1992) showed that EPIC N leaching estimates can be very sensitive to choice of evapotranspiration routine and soil moisture estimates. Roloff, de Jong, and Nolin (1998b) found that EPIC N leaching estimates were also very sensitive to several input parameters, including curve number, precipitation, solar radiation, and soil bulk density. Engelke and Fabrewitz (1991) found that EPIC estimates of denitrification and mineralization were plausible; however, Richter and Benbi (1996) described EPIC's mineralization predictions as very poor. Edwards

TABLE 3. Example nutrient cycling and/or nutrient loss scenario studies

Region/Location	Description/Indicators Assessed	Source
Rockingham County, Virginia	N runoff and leaching losses from manure and fertilizer applications for 120 cropland sites; 44 years (1949-92)	Parsons, Pease, and Martens (1995)
Texarkana, Fayettville, and Stuttgart, Arkansas	Sediment; organic N; nitrate and soluble P in runoff; total P; poultry manure applied to hypothetical fields (50 years)	Edwards, Daniel, and Marbun (1992)
12-state U.S. north central region	N leaching and N runoff losses using EPIC metamodels based on 30-yr EPIC runs; ~130,000 NRI cropland points	Wu and Babcock (1999)
East River Watershed near Green Bay, Wisconsin	Sediment P, soluble P, and total P from dairy manure and fertilizer; total field area = 1272 ha; 42 years	Sugiharto et al. (1994)
Lithuania; representative agricultural regions	N and P losses from applications of fertilizers; 17 years	Tumas (2000)
Oklahoma Panhandle region	Crop yields; N leaching losses in response to different irrigation practices; 20 years	Geleta et al. (1994)
Upper Mississippi Valley	Crop yields; N runoff losses and organic N losses; 1,500 EPIC simulations that were representative of region	Atwood et al. (1999)

et al. (1994) found that annual EPIC estimates of nutrient losses were significantly correlated with measured values, except for nitrate-N. Relatively strong agreement was found by Pierson et al. (2001) between EPIC-predicted and measured phosphorus (P) losses in runoff, but predictions for single events were not as accurate. Long-term trends were accurately predicted by EPIC for conditions at Treynor, Iowa (Chung et al., 1999), although predicted annual losses were not as accurate. EPIC output did not compare well with measured in-stream loads for two large Lake Erie subwatersheds (Forster et al. 2000), but relative results were correctly predicted except for soluble P.

The studies listed in Table 3 point to the fact that EPIC has been applied to a wide range of nutrient management scenarios, in terms of both specific management practices and simulation scales. Further confirmation of the versatility of EPIC for nutrient management scenarios can be seen from the various studies described in the Economic and Environmental Studies and Comprehensive Regional Assessments sections.

Wind and Water Erosion Studies

Assessment of erosion losses and erosion impacts on crop productivity are key processes that have been present in EPIC since its inception. The Onstad-Foster (AOF) version of the Universal Soil Loss Equation (USLE) equation (Williams, Jones, and Dyke 1984) and the Modified USLE (MUSLE) were provided as options to estimate water erosion in the original EPIC model. The standard USLE was added later in the 1980s and by the mid-1990s three additional erosion equations had also been incorporated into EPIC (Williams 1995): two MUSLE variants referred to as MUST and MUSS, and a fourth MUSLE option called MUSI that requires input coefficients. The energy component is the only difference between the six USLE-based equations. The RUSLE erosion estimation method (Renard 1997) was incorporated later into the model, providing a seventh option for estimating water erosion. The original wind erosion model used in EPIC was the WEQ (Williams 1995), which has since been replaced by the Wind Erosion Stochastic Simulator (WESS) approach (Potter et al. 1998). Numerous EPIC applications have been performed for soil erosion; example applications are presented here, including validation and scenario studies.

Water Erosion Validation and Scenario Studies

King, Richardson, and Williams (1996) used MUSS to simulate non-calibrated erosion in response to no-till and conventional tillage for six small watersheds located near Riesel, Texas, in the Blacklands Prairie region of central Texas. The replicated annual means and standard deviations of surface runoff and erosion agreed closely with the corresponding measured values, and significant correlation was also found for monthly values. Purveen et al. (1997) reported that the EPIC MUSS option satisfactorily replicated snowmelt-induced runoff and erosion measured on plots near La Grace, Alberta. Median erosion rates of 58.8 and 3.6 t/ha were estimated with the EPIC USLE option by Chung et al. (1999) for two watersheds in southwest Iowa that were cropped in continuous corn during the years 1976-87 and managed with conventional tillage and ridge tillage, respectively. The estimated erosion rates clearly captured the effects of the two different tillage systems and also compared favorably with average sediment delivery ratio (SDR) estimates determined over the 1969-84 period, for sediment delivery to gulley headcuts located at the watershed outlets. Reyes et al. (2004) found that EPIC and three other models did not satisfactorily simulate runoff

and erosion measured near Greensboro, North Carolina, during a 17-month period; however, no calibration of the models was performed prior to the simulations. Bhuyan et al. (2002) found that EPIC and two other models satisfactorily simulated the erosion effects of three different tillage systems for a site near Ottawa, Kansas. Schaub, Meier-Zielinski, and Goetz (1998) found that the EPIC USLE option was able to generate erosion rates comparable to those observed in three regions of Switzerland, but only after calibration of the USLE rainfall erosivity factor (R) was performed. Favis-Mortlock (1998) evaluated EPIC and five other models with 73 site-years of runoff and erosion data from seven sites in three countries. He concluded that calibration can improve model results, that best results are generally obtained for long-term simulations, and that calibrated models are especially capable of predicting strongly correlated relative results. Average annual erosion rates predicted with EPIC by Poudel, Midmore, and West (2000) ranged from 28.1 to 98.3 t/ha for rotations of cabbage-tomato-cabbage and tomato-cabbage-tomato, respectively, for slopes that spanned 15% to 65% in the Manupali Watershed in northern Mindanao in the Philippines. The simulated erosion rates corresponded well with measured values and helped support farmer participatory research efforts in the region.

Crop productivity was assessed by Benson et al. (1989) by simulating annual crop production in EPIC for 100 years, for four soils representing the eastern areas of Colorado, Washington, or Iowa, or the Georgia Piedmont region. One key result of their analysis was that the potential productivity gain from using conservation tillage in tandem with conservation practices was greater than twice that predicted for conventional tillage for three of the four soils. An EPIC assessment was performed by Wingard (1996) of typical agricultural cropping systems and practices that were used by the Mayan culture during the Late Classic Period (A.D. 700-900) in the Copán Valley of Honduras. A major finding of the study was that environmental degradation due to soil erosion played an important role in the development and collapse of the Mayan civilization in the Copán Valley. Hypothetical 100-year scenarios conducted with EPIC for a 1 ha field in the Baldegg Watershed in Switzerland indicated that greater crop productivity decline would take place if soil erosion were occurring (Schaub, Meier-Zielinski, and Goetz 1998). Jain and Dolezal (2000) evaluated water erosion impacts with multiple EPIC erosion options for 18 fields located in the 1.42 km2 Cernici Watershed, which lies in the foothills region

of Central Bohemia, Czech Republic. Variable results occurred depending on whether the USLE, MUSLE, or AOF methods were used. Lee, Phillips, and Liu (1993) assessed the impacts of four tillage/cover crop scenarios on soil water erosion in the U.S. Corn Belt by performing 100-year EPIC simulations with the MUSLE option for 100 statistically selected NRI points that were cropped in corn or soybeans in 1987. They found that increases in conservation tillage would result in substantial decreases in water erosion. Lakshminarayan and Babcock (1996) evaluated the effects of soil erosion for the complete set of cropland NRI points in the U.S. 12-state North Central region with metamodels that were created from a smaller set of EPIC simulations. They found that water erosion was a greater problem than wind erosion for most of the region, that the simulated erosion results agreed well with NRI erosion estimates, and that greater adoption of conservation practices would be very cost effective.

Climate change impacts on soil erosion have also been estimated with EPIC. Favis-Mortlock et al. (1991) simulated climate change effects represented by 18 scenarios of increased temperature, increased or decreased precipitation, and two atmospheric CO_2 levels of 330 or 660 ppm, for a site located in the English South Downs region near Brighton, United Kingdom. Soil erosion was predicted to increase up to 64% over baseline levels because of increased precipitation; this increase declined because of higher yields when atmospheric CO_2 was simulated at 660 ppm. Slight erosion reductions were predicted for some of the scenarios driven by projected decreased rainfall. Further simulations performed by Favis-Mortlock and Boardman (1995) with EPIC for the English South Downs indicated that erosion rates would increase at a faster rate in wet years versus dry years in a future "wetter climate" and that annual erosion would increase 150% in response to a 10% increase in precipitation. Soil erosion effects predicted with EPIC by Lee, Phillips, and Dodson (1996), using the same framework for the U.S. Corn Belt and 36 hypothetical climate scenarios reported by Phillips, Lee, and Dodson (1996), included the following: (1) soil erosion increased at twice the rate of the precipitation increase; (2) water erosion decreased by 3%-5% and wind erosion increased by 15%-18% (and soil erosion increased overall) in response to a 2% temperature increase; and (3) water erosion did not change while wind erosion decreased 4%-11% when an increase of atmospheric CO_2 from 330 to 625 ppmv was factored into the temperature increase sce-

nario. Díaz et al. (1997) found that there would be little increase in erosion for soils in the Rolling Pampas region of Argentina based on EPIC simulations driven by a GCM scenario. Climate change impacts on agricultural production were also evaluated with EPIC as reported in Lee, Phillips, and Benson (1999).

Wind Erosion Validation and Scenario Studies

Very few validation studies of the EPIC wind erosion model have been performed. Potter et al. (1998) tested the EPIC wind erosion model with measured data collected during April 1992 near Lethbridge, Alberta. Wind erosion was predicted on each day that wind erosion was actually measured and the magnitude of the simulated erosion was similar to the measured levels for six of the seven events. Van Pelt et al. (2004) found that the EPIC wind erosion equation underpredicted nine events, accurately predicted eight events, and overpredicted seven events for 24 wind erosion storms that occurred over a seven-year period at Big Springs, Texas. The model tended to underpredict large storm events (>10 t/ha) and overpredict small storms.

Estimation of wind erosion was performed for conditions representative of southwest Niger using windspeed data collected at the ICRISAT Sahelian Center, creating crop parameters for millet, and modifying the EPIC code (with WEQ) and/or input data to account for crop wind abrasion and other pertinent local conditions (Michels, Potter, and Williams 1997). A 10-year simulation (1984-94) was performed that indicated wind erosion events occurred in the 1980s but not in the first half of the 1990s and that wind abrasion damage decreased as plant size increased. Gaiser et al. (2003) have performed further research with an older version of EPIC (that used WEQ) that confirmed the need to have vegetative cover to prevent soil degradation occurring from wind erosion in Niger. Izaurralde et al. (1997) estimated wind and water erosion for the agricultural region of the Canadian Prairie Provinces (30 million ha) using metamodels developed by Lakshminarayan et al. (1996) that were constructed from 22,000 EPIC simulations. Wind and water erosion rates were found to be generally consistent with other erosion estimates for the region, with wind erosion being more dominant in Manitoba and Saskatchewan while water erosion was more important in Alberta. Wang et al. (2002) performed several 60-year EPIC scenarios for Wuchuan County in Inner Mongolia, China, to determine the effects of different crop residue removal strategies on wind erosion. Wind erosion was

predicted to decline by up to 60% when crop residue was preserved until zone tillage (alternating 0.5 m strips) was performed. Delays of crop residue removal resulted in predicted wind erosion declines of 35% to 46%.

Soil Carbon Sequestration

Interest is growing in evaluating and developing agricultural management practices that are effective at sequestering carbon in soil to help mitigate atmospheric CO_2 levels. Several soil organic carbon (SOC) sequestration studies were performed with the original EPIC carbon cycling routine, which was simulated in a relatively simplistic fashion as a function of soil nitrogen levels. Soil carbon sequestration was estimated with EPIC for the previously described studies performed by Lee, Phillips, and Liu (1993) and Lee, Phillips, and Dodson (1996) for the U.S. Corn Belt region. Maintaining status quo cropping and management practices were predicted in both studies to result in significant declines in future soil carbon levels; Lee, Phillips, and Dodson estimated that 50% of the SOC losses were due to soil erosion. Lee, Phillips, and Liu found that only increased no-till adoption with a winter wheat cover crop would lead to an annual increase in carbon (0.1x106 tons). Lee, Phillips, and Dodson further found that hypothetical increases in temperature and precipitation accelerated SOC losses while increased atmospheric CO_2 slowed SOC loss rates. The effects of four scenarios (including baseline conditions) on SOC were evaluated by Mitchell et al. (1998) with EPIC metamodels for cropland NRI points in the 12-state North Central region. All four scenarios were projected to result in SOC declines; limiting soil losses to below soil-specific soil loss "T standards" was predicted to result in lower SOC loss rates than a 50% increase in conservation tillage adoption. Roloff, de Jong, and Nolin (1998b) found that the original EPIC methodology satisfactorily estimated total SOC content for a long-term spring wheat rotation at Swift Current, Saskatchewan. Campbell et al. (2000) used EPIC to estimate SOC reductions by water and wind erosion, as part of an overall carbon balance study at Swift Current, Saskatchewan.

A major revision of the EPIC carbon cycling routine was performed by Izaurralde et al. (2001) and Izaurralde et al. (2004) based on concepts used in the Century model (Parton et al. 1994; http://www.nrel.colostate.edu /projects/ century5/reference/index.htm). In the revised approach, simulated carbon and nitrogen compounds are stored in either biomass, slow, or passive soil pools. Direct interaction is simulated between these pools and

the EPIC soil moisture, temperature, erosion, tillage, soil density, leaching, and translocation functions. Carbon leaching from surface litter to deeper soil layers and the effect of soil texture on organic matter stabilization are also both accounted for in the revised code. Initial tests of the improved carbon cycling routine have been performed by Izaurralde et al. (2001) and Izaurralde et al. (2004) for five Great Plains sites located in Nebraska, Kansas, and Texas, and for a 60-year rotation experiment located near Breton, Alberta. It was concluded from these studies that the model satisfactorily replicated the soil carbon dynamics over a range of environmental conditions and cropping/vegetation and management systems. It was further concluded by Apezteguía, Izaurralde, and Sereno (2002) that the revised EPIC carbon cycling routine performed robustly for simulations of deforested conditions, cropping systems, and native vegetation in the Córdoba region of Argentina. Simulations performed for Iowa (~12,000 NRI points) by Zhao, Kurkalova, and Kling (2004) with the revised EPIC model resulted in an average annual SOC rate of 50.6 g/m^2 in response to conservation tillage (mulch till and no-till), which compares favorably with SOC rates reported by Lal et al. (1998) and West and Post (2002) for similar tillage systems. EPIC carbon estimates obtained with the National Nutrient Loss Database (NNLD) modeling system (Potter et al. 2004) have also compared well with values reported in the literature.

Economic and Environmental Studies

As noted previously, Ellis et al. (1993) and Gray et al. (1997) coupled EPIC with the FLIPSIM whole-farm model to perform economic analyses of irrigated agriculture in Texas. Interfaces between EPIC and economic models have been performed for several other studies (Table 4), including a number of economic-environmental analyses. The focus of most of these studies was to compare net returns and/or other economic indicators versus erosion, nutrient loss, or other environmental indicators predicted by EPIC, in response to alternative cropping systems, management practices, and other scenarios. For example, Kurkalova, Kling, and Zhao (2004) estimated the total sequestered carbon and nitrogen runoff, water erosion, and wind erosion reductions that would occur in Iowa in response to varying rates of conservation tillage adoption; the adoption rates were determined as a function of 40 different hypothetical budgets ranging from $2 to $80 million that could be potentially administered to Iowa farmers through the Conservation Security

TABLE 4. Example studies using a combined EPIC-economic analysis approach

Region/Location	Economic Approach	Objective	Source
U.S. Central High Plains (125,000 km2 overlying the High Plains Aquifer)	Five regional mathematical programming models	Evaluate cost and envr. impact (on groundwater) for alternative scenarios	Bernardo et al. (1993)
Walnut Creek Watershed, IA (5,138 ha)	Crop prices and production costs (enterprise budgets)	Assess economic and envr. impacts of three alternative landscape scenarios	Coiner et al. (2001)
Argentine Pampa subregion (3 rep. farms)	Three representative farm models (profit maximizing)	Economic change effects at farm and regional levels	Deybe and Flichman (1991)
Western Lake Erie Basin (100 representative farms)	Farm-level integer prog. (profit maximizing) model	Assess factors affecting relative overall efficiency and return on assets	Forster (2002)
Willamette Valley, OR (five representative farms)	Economic optimization model of farm-level behavior	Assess responses to nutrient and soil erosion control policies	Taylor, Adams, and Miller (1992)
Eastern Corn Belt (two representative farms)	Crop budget analysis plus yield estimates from EPIC	Assess econ. and envr. multi-attribute rankings of different cropping systems	Foltz et al. (1995)
Hypothetical southwest OK irrig. district (18,000 ha)	Linear programming model; maximize net revenue	Optimize intra- and inter-seasonal irrigation water allocations	Evers, Elliott, and Stevens (1998)
Portion of Southern High Plains in north TX (2.6 million ha)	North and south subregion mathematical programming models	Evaluate policy alternatives designed to attain specific water quality goals	Wu et al. (1995)
Mafraq region of Jordan	Whole farm economic model (FPPME linear programming model)	Determine sustainable dry- land farming practices in a low rainfall region	Hughes et al. (1995)
State of Iowa (12,000 NRI database points)	Discrete-choice adoption model	Estimate multiple benefits of practice- and performance-based policies	Kurkalova, Kling, and Zhao (2004)
Northern Tunisia (486 ha farm)	Multi-objective programming model (MOPM)	Assess econ. and envr. effects of reducing N, sediment, and other pollution	Mimouni, Zekri, and Flichman (2000)

Program of the 2002 U.S. farm bill. Other examples of studies that incorporated both EPIC and an economic model are Shankar et al. 2000; Lakshminarayan et al. 1991; Bryant et al. 1993; Bernardo et al. 1993; Foltz, Lee, and Martin 1993; Chang et al. 1994; Teague, Bernardo, and Mapp 1995; Kelly, Lu, and Teasdale 1996; Chowdhury and Lacewell 1996; Van Dyke et al. 1999; Savard 2000; Rejesus and Hornbaker 1999; Pautsch et al. 2001; Feng et al. 2004; and Zhao, Kurkalova, and Kling 2004).

Comprehensive Regional Assessments

The EPIC model has been used in a number of large regional applications to evaluate the impacts of cropping systems, management practices, and environmental conditions on multiple environmental indicators. Many of these studies have been focused on evaluating specific agricultural policy options, including several efforts performed by governmental agencies such as USDA's Natural Resources Conservation Service (NRCS). The first application of EPIC by the NRCS (formerly the Soil Conservation Service or SCS) was to evaluate the potential loss in cropland productivity into the future for the second RCA. That evaluation initiated a shift in U.S. policy from focusing on the on-site productivity losses due to soil erosion to the off-site water quality impacts. EPIC has since been used in two ways at the NRCS: (1) stand alone modeling where the model is applied and results are used directly in reports; and (2) development of coefficients for use in economic models to reflect the differing environmental performance of alternative agricultural technologies. One key set of NRCS EPIC applications has been the evaluation of the 1985, 1990, 1996, and 2002 farm bill proposals, which required nationwide EPIC per acre erosion, crop yield, and nutrient leaching and runoff estimates in response to projected changes in land use, effects of commodity or income subsidies, and the impacts of erosion control practices. The majority of these and other EPIC-based studies have been conducted for internal NRCS agency use and many have yet to be published.

Other comprehensive regional EPIC studies have been performed including those listed in Table 5. For example, Bernardos et al. (2001) analyzed agroecological change that occurred in the La Pampas region of the Argentine Pampas. Validation was performed by comparing EPIC output versus statistical crop yield data, historical soil erosion accounts, and experimental hydrologic and N flux data. The model was found to be useful for

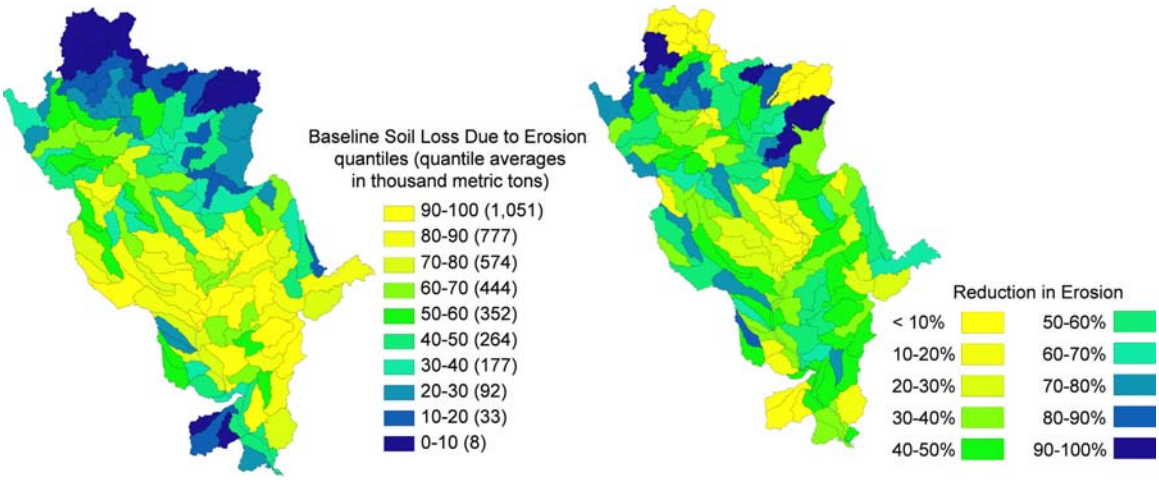
TABLE 5. Examples of comprehensive regional EPIC studies

Region/Location	Description/Indicators assessed	Source
Portion of Argentine Pampas La Pampa province (~1 million ha)	Hydrologic balance indicators, crop yields, wind and water erosion, N and P cycling and losses	Bernardos et al. (2001)
Trinity River Basin, Texas (~47,000 km^2)	Crop yields, runoff, water erosion, N and P losses in runoff and sediment; N leaching	Chen et al. (2000)
U.S. Cropland (12 main crop) east of the Rocky Mountains (~1.2x106 km2)	Crop yields, water erosion, N and P losses in runoff and on sediment, N leaching	Potter, Atwood, and Goss (2001)
U.S. Cropland for 16 main crops (~1.35x106 km^2)	Thirty indicators including crop yields; hydro. bal. indicators; N and P losses in runoff, on sediment, and via leaching; oxidized carbon; and soil carbon	Potter et al. (2004)
U.S. 12-state North Central Region	Wind and water erosion; soil carbon; N leached and in runoff; atrazine leached, volatilized, and in runoff	Babcock et al. (1997), Gassman et al. (1998)
Illinois cropland area (represented by 100 NRI points)	Crop yields, water erosion, N and P losses in runoff and on sediment, N leaching	Phillips et al. (1993)

performing ecological interpretations and assessments. Various software tools have also been developed to support regional EPIC studies, such as the interactive EPIC (i_EPIC) software package (Gassman et al. 2003a; http://www.public.iastate.edu/~elvis) that has been used to support large EPIC simulation sets such as those performed by the NRCS with the NNLD system (Potter, Atwood, and Goss 2001; Potter et al. 2004), assessments for the Upper Mississippi River Basin (Figure 1) and the larger 12-state North Central region (Babcock et al. 1997; Gassman et al. 1998; Kling et al. 2004), and global representative farm studies (Figure 2) (Thomson, Izaurralde, and Rosenberg 2002) that will facilitate analysis of variations in management, cropping systems, and climate conditions for major agricultural production regions across the globe.

Other Adaptations and Interface Applications

The incorporation of pesticide fate components from the GLEAMS model into EPIC (Table 1) is described in Sabbagh et al. (1991). Applications of EPIC for pesticide movement and losses have been performed by Williams, Richardson, and Griggs (1992) and Sabbagh et al. (1992). Sabbagh, Bengston, and Fouss (1991); Sabbagh, Fouss, and

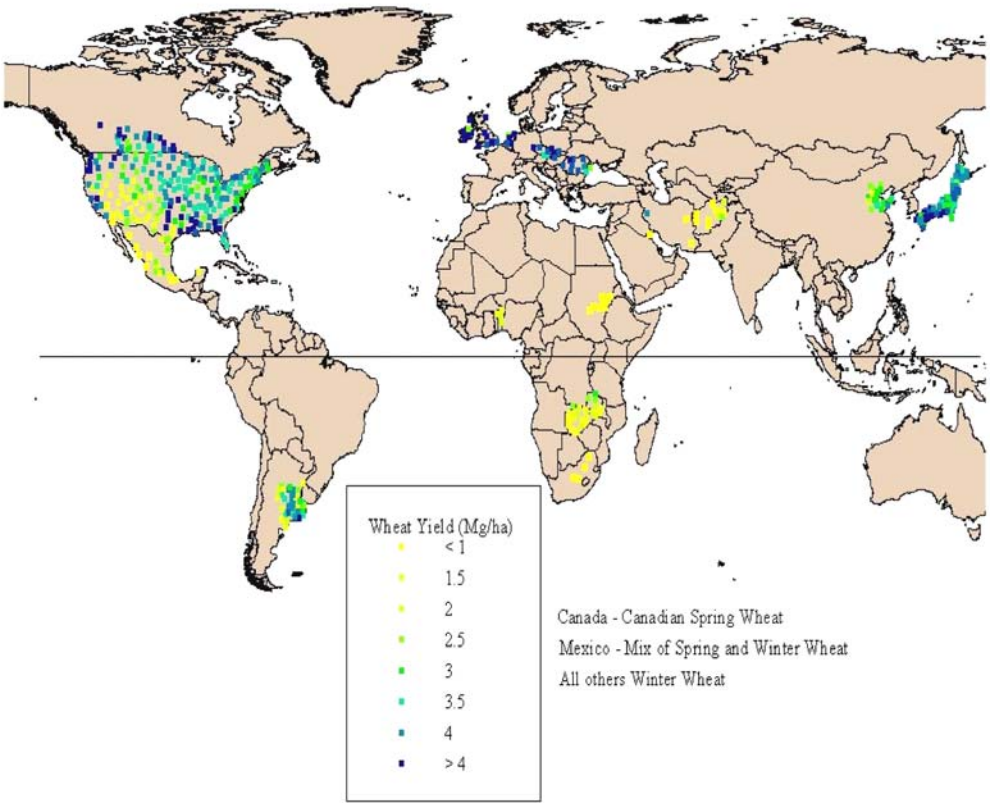


(a) Baseline aggregate erosion levels (b) Erosion reductions due to the scenario

Note: The simulations were performed for approximately 29,000 1997 NRI cropland points within the Upper Mississippi River Basin (UMRB), that are presented at an aggregated level for the 131 U.S. Geological Survey (USGS) 8-digit watersheds located in the UMRB: (a) quantiles of total soil erosion losses estimated for all cropland in each 8-digit watershed, and (b) estimated reduction in total soil erosion losses in response to a hypothetical scenario in which roughly 9% of the total 1997 UMRB cropland area was assumed shifted to the USDA Conservation Reserve Program (CRP) in combination with increased adoption of conservation tillage practices that were assumed to occur on an additional 22% of the 1997 cropland area, that was managed with conventional tillage in the baseline (Kling et al. 2004).

FIGURE 1. Results of EPIC USLE simulations

Bengston (1993) also created EPIC-WT, which included a tile drainage component that was based on the approach used in the DRAINMOD model; this modification was never adopted in the standard EPIC model. Other adaptations of EPIC and/or interfaces of EPIC with other models include (1) a "spatial EPIC" system (Priya and Shibasaki 2001) that links geographical information systems (GIS) input for large regional studies (e.g., India) and includes an adaptation loop to temporally evaluate management practices; (2) the use of EPIC components (or interfaces with EPIC) in the ECOPHYS tree growth process model (Host et al. 1996), the Pat-GEM ecosystem model (Binder, Boumans, and Costanza 2003), the GPFARM modeling system (Andales, Ahuja, and Peterson 2003), and a large watershed N modeling system (Lunn et al. 1996); (3) improvements in climate inputs (Weiss et al. 2001; Cooter and Dhakhwa 1995); and (4) the use of EPIC in a GIS-based decision support system (Rao, Waits, and Neilsen 2000).



Source: Thomson, Izaurralde, and Rosenberg 2002.

FIGURE 2. Dryland wheat yields estimated with the JGCRI EPIC farm models for global baseline climate, soil, and management conditions

Overview of APEX

The APEX model operates on a daily time step and allows simultaneous simulation of multiple subareas for a wide range of soil, landscape, climate, crop rotation, and management practice combinations. A subarea can be defined as a livestock feeding area, crop field, field or buffer strip, or some other portion of a larger watershed or farm. It can be applied for whole-farm or small watershed (up to 2,500 km^2) analyses and can be used for innovative applications, such as filter strip impacts on nutrient losses from manure application areas, that require the configuration of at least two subareas. Alternatively, it can be run for single fields in the same manner that is allowed in EPIC. The APEX structure is similar to EPIC and includes the same nine major components as previously described. Additional functions included in APEX include routing of flows and pollutant

loads between subareas to a watershed outlet and a manure management routine that supports simulation of liquid waste applications from concentrated animal feeding operations' waste storage ponds or lagoons, and stockpiling of solid manure from feedlots or other animal feeding areas and subsequent land application. The latest version of APEX has also been updated with the improved carbon cycling routines developed by Izaurralde et al. (2001). Further description of the APEX components is given in Williams et al. (1995), Williams, Arnold, and Srinivasan (2000), and Williams (2002).

APEX Applications Within the NPP

The CEEOT-LP integrated modeling system was developed for the NPP to facilitate holistic watershed economic and environmental analyses through a farm-level economic model and an environmental component consisting of APEX and the Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998), especially for watersheds with intensive livestock production. The environmental component was designed to facilitate a wide range of field-scale manure application scenarios coupled with the ability to simulate nutrient and sediment movement through an entire watershed. The basic approach is to simulate land application of manure at a field scale in APEX, input the edge-of-field nutrient loadings in both the solution and sediment phases into SWAT, and then simulate the subsequent routing of the nutrient loadings through a stream system and ultimately to a watershed outlet. Simulation of fertilizer inputs to cropland or pasture land are also simulated in both APEX and SWAT as appropriate. Further description of the overall system is given in Osei, Gassman, and Saleh (2000) and Gassman et al. (2002).

Initial testing and calibration of the APEX model was performed using monitoring data collected over periods ranging from 12 to 20 months for eight research plots that were located in or near the Upper North Bosque River Watershed (UNBRW) that included a range of crop, soil, landscape, and manure management conditions representative of the watershed (Flowers, Williams, and Hauck 1996). It was concluded that APEX was an appropriate tool for simulating manure management practices associated with different policy scenarios, given that it replicated the measured runoff, sediment, and nutrient losses with reasonable accuracy and that it captured the proper relative response of different runoff parameters. Further evaluation and calibration of APEX was performed by Gassman (1997) for UNBRW baseline conditions by perform-

ing separate 30-year simulations for individual manure waste application fields associated with all 94 dairies that were present in the watershed at the time of the study. Calibration and validation of APEX was also indirectly performed for the UNBRW by executing APEX in tandem with SWAT and subsequently comparing the SWAT output with in-stream flow, sediment, and N and P measurements at the watershed outlet and other up-stream locations (Saleh et al. 2000). The predicted SWAT flow, sediment, and nutrient losses compared favorably with corresponding measured values, indicating that APEX simulated losses from the complete set of UMBRW dairy waste application fields with adequate accuracy.

Following calibration, APEX was applied within CEEOT-LP for a suite of manure management scenarios (Osei, Gassman, and Saleh 2000) for the UMBRW. Results for selected scenarios are reported in Osei et al. (2000), Gassman et al. (2002), and Osei et al. (2003b); results for the complete set of simulated scenarios are given in Pratt, Jones, and Jones (1997). Edge-of-field APEX results reported in Osei et al. (2000) indicate that shifting from N-based to P-based manure application rates or adopting solid manure composting would result in aggregate P loss reductions of 14% to 86% at the waste application field level. However, aggregate net returns were predicted to decline by 7% to 30%. Incorporation of manure with a tandem disk on fields double-cropped with sorghum and winter wheat was projected by APEX to result in an aggregate 37% reduction of total P loss as compared with simulated surface manure applications (Osei et al. 2003b).

Further applications of APEX within CEEOT-LP have been performed for the Lake Fork Reservoir Watershed (LFRW) in northeast Texas, the Upper Maquoketa River Watershed (UMRW) in northeast Iowa, and the Mineral Creek Watershed (MCW) in eastern Iowa. Generic field configurations were developed for dairy farms in the LFRW and several different types of livestock farms in the UMRW and MCW in order to perform the APEX simulations for each watershed (Osei, Gassman, and Saleh 2000; Gassman et al. 2002; Gassman et al. 2003b). Only limited calibration of APEX was performed for the LFRW and UMRW because of a lack of field- and watershed-level monitoring data at the time of the studies (Gassman et al. 2002); calibration data was also lacking for the MCW. Stocking density and rotational grazing scenarios were predicted to reduce total P losses at the LFRW outlet by 23% to 64% and result in total N loss changes of +1% to -10%,

relative to baseline conditions (Gassman et al. 2002; Osei et al. 2003a). No-till, reduced fertilizer, and P-based manure application scenarios were predicted to reduce total P and N losses at the UMRW outlet by 7% to 32% and 9% to 33%, respectively. Terraces and grassed waterways were predicted to have the largest impacts on sediment and nutrient load reduction at the MCW outlet. McNitt et al. (1999), Keith et al. (2000), and Gassman et al. (2003b) present results for the complete set of the LFRW, UMRW, and MCW scenarios, respectively.

Other APEX Applications

An APEX validation study was performed by Ramanarayanan et al. (1997) who simulated the UNBRW North Fork and Goose Branch subwatersheds (each about 1,500 ha in size) by subdividing them into 26 and 43 subareas, respectively, and determining the dominant land use and soil type in each subarea, including dairy waste application fields. The mean simulated runoff volumes, total suspended solids, and nutrient losses matched the corresponding measured values well. Monthly flow volumes were also generally well simulated but correlations between the predicted and observed monthly sediment and nutrient loads were relatively weak. In a companion study, Williams et al. (1997) performed five 30-year alternative management scenarios in APEX to evaluate their effectiveness in reducing sediment and nutrient losses for the Goose Branch subwatershed. It was concluded from the simulation results that adopting appropriate agronomic practices (e.g., overseeding summer crops with a winter crop) and manure application strategies, across the entire watershed, could greatly reduce nutrient losses and mitigate the need for a more expensive manure haul-off solution.

Gassman et al. (2001) compared the results of using a coupled APEX-SWAT approach versus SWAT by itself (SWAT-only) for simulating broiler litter applications associated with eight broiler operations located in the Duck Creek Watershed (DCW) that drains 39,000 ha in east central Texas. Both approaches were found to be viable alternatives for simulating nutrient movement in the DCW; the most accurate results were obtained for the SWAT-only method, which was probably due in part to more extensive calibration efforts. Benson et al. (2000) performed an analysis of livestock manure recycling practices, and the resulting environmental and economic impacts of adopting such management strategies, by interfacing APEX and FLIPSIM for representative broiler farms in the Missouri counties of

Newton and McDonald. A scenario in which litter was applied triennially (80 pounds of N were applied in years when litter was not applied) to a 200 ac pasture that was grazed 150 days per year by 300 stock cattle was predicted to provide the greatest farm income and the lowest P loss and top 6 inch soil P accumulation.

APEX has also been applied for herbicide and forestry scenarios. An APEX watershed study was performed by Harman, Wang, and Williams (2004), who evaluated alternative runoff control practices for atrazine use in corn and sorghum production for the Aquilla Watershed that covers almost 66,000 ha in central Texas. The dominant land use and soil type were again configured in APEX for each of the 44 subareas delineated for the watershed. Constructing sediment ponds, establishing grass filter strips, banding a 25% rate of atrazine, and constructing wetlands were found to be the four most effective practices. Saleh et al. (2004) applied APEX for an assessment of silvicultural practices on streamflow, sediment loads, and nutrient losses for nine small watersheds (2.6 to 2.8 ha in size) located in southwest Cherokee County in eastern Texas. Several hydrologic modifications were made to the APEX canopy, litter, and soil storage routines to improve the model's ability to replicate forest hydrologic conditions. The performance of APEX was judged to be reasonable based on comparisons between predicted and observed storm runoff, peak flow rates, and sediment and nutrient losses, especially considering the small magnitude of forest pollutant losses relative to agricultural nonpoint source pollution loadings.

Emerging EPIC and APEX Applications

The EPIC and APEX models will undoubtedly continue to be used for a wide range of studies similar to those described here. Two emerging application domains are (1) climate change impacts on crop yields, hydrologic balance erosion losses, and other pollutant losses; and (2) estimation of SOC levels in response to different cropping systems, management practices, and environmental conditions. To date, the majority of climate change studies have focused only on crop yield impacts with EPIC; future global change studies will need to incorporate more complete impact analyses that include a full set of environmental indicators as well as yield estimates at both the field and regional scale. Global climate change and SOC studies with APEX are also anticipated, especially for farm- and watershed-level systems that are dominated by livestock production. Large national- or regional-scale APEX applications are being developed, similar to some of the

EPIC studies described here. These include an adaptation of the NNLD to support APEX buffer strip assessments for U.S. cropland regions and the interface of APEX and FEM within the CEEOT macro-modeling system (CEEOT-MMS) by the Texas Institute for Applied Environmental Research at Tarleton State University. The CEEOT-MMS has already been used for an assessment of manure application practices for animal feeding operations for the entire state of Texas (Osei et al. 2004), and future applications of the system will be expanded to other U.S. regions and to a wider range of environmental indicators. Other novel applications and adaptations can also be expected to unfold in future use of EPIC and APEX, such as the continued work on assessments of ancient Mayan agriculture by Hayes and Wingard (2002), who build on the work of Wingard (1996) by simulating the effects of "Milpa" (Atran 1993) and other cropping systems in EPIC that were likely used by the Mayan people in Belize.

Conclusions

Both the EPIC and APEX models have proven to be robust tools for simulating the effects of crop rotation, tillage, and other management practices, climate, soil, and topography on crop yields, water and wind erosion, nutrient and pesticide losses, and SOC content. The models have been used and adapted for agricultural regions throughout North America and in many other regions around the globe, including numerous studies focused on the environmental and/or economic impacts of alternative agricultural policies or management strategies. The results of many studies described here indicate that calibration of the models is often required to obtain optimum results, and in some cases revisions of input parameters or modifications to the code are required to achieve adequate results or to perform desired analyses. The applications reviewed also reveal that EPIC and APEX are most effective at simulating the long-term impacts of different cropping systems and management practices, and that the models are less accurate at replicating the effects of single climatic events on erosion and other losses or interannual variability between crop yields and pollutant losses. Ongoing research is needed to improve the prediction capabilities of both models, including the ability to capture yield variability and other effects that are not well simulated by the current versions of the models.

References

Adams, R.M., L.L. Houston, B.A. McCarl, M. Tiscareño, J. Matus, and R.F. Weiher. 2003. "The Benefits to Mexican Agriculture of an El Niño-Southern Oscillation (ENSO) Early Warning System." *Agric. Forest Meteor.* 115: 183-94.

Andales, A.A., L.R. Ahuja, and G.A. Peterson. 2003. "Evaluation of GPFARM for Dryland Cropping Systems in Eastern Colorado." *Agron. J.* 95: 1510-24.

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, Argentina." *Agronomy Abstracts*. CD-ROM.

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

Atran, S. 1993. "Itza Maya Tropical Agro-Forestry." *Current Anthro.* 34(5): 633-700.

Atwood, J.D., V.W. Benson, R. Srinivasan, C. Walker, and E. Schmid. 1999. "Simulated Nitrogen Loading from Corn, Sorghum, and Soybean Production in the Upper Mississippi Valley." In *Sustaining the Global Farm: Selected Papers from the 10th International Soil Conservation Organization Meeting*, pp. 344-48 Edited by D.E. Stott, R.H. Mohtar, and G.C. Steinhardt. West Lafayette, IN: U.S. Department of Agriculture, Agricultural Research Service, National Soil Erosion Lab, Purdue University. http://topsoil.nserl.purdue.edu/nserlweb/isco99/pdf/ISCOdisc/tableofcontents.htm (accessed July 27, 2004).

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

Beckie, H.J., A.P. Moulin, C.A. Campbell, and S.A. Brandt. 1995. "Testing Effectiveness of Four Simulation Models for Estimating Nitrates and Water in Two Soils." *Can. J. Soil Sci.* 75: 135-43.

Benson, V.W., K.N. Potter, H.C. Bogusch, D. Goss, and J.R. Williams. 1992. "Nitrogen Leaching Sensitivity to Evapotranspiration and Soil Water Storage Estimates in EPIC." *J. Soil Water Cons.* 47(4): 334-37.

Benson, V.W., O.W. Rice, P.T. Dyke, J.R. Williams, and C.A. Jones. 1989. "Conservation Impacts on Crop Productivity for the Life of a Soil." *J. Soil Water Cons.* 44(6): 600-4.

Benson, V.W., P.T. Zimmel, A. Bross, D.L. Schuster, and J. Trujillo. 2000. "Newton and McDonald Counties Contract Broiler Representative Farm." FAPRI-UMC Report #08-00. Food and Agricultural Policy Research Institute, University of Missouri, Columbia.

Bernardo, D.J., H.P. Mapp, G.J. Sabbagh, S. Geleta, K.B. Watkins, R.L. Elliott, and J.F. Stone. 1993. "Economic and Environmental Impacts of Water Quality Protection Policies," pt. 2, "Application to the Central High Plains." *Water Resour. Res.* 29(9): 3081-91.

Bernardos, J.N., E.F. Viglizzo, V. Jouvet, F.A. Lértora, A.H. 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.

Bhuyan, S.J., P.K. Kalita, K.A. Janssen, and P.L. Barnes. 2002. "Soil Loss Predictions with Three Erosion Simulation Models." *Environ. Model. Software* 17(2): 135-44.

Binder, C., R.O. Boumans, and R. Costanza. 2003. "Applying the Patuxent Landscape Unit Model to Human Dominated Ecosystems: The Case of Agriculture." *Ecol. Model.* 159: 161-77.

Bouniols, A., M. Cabelguenne, C.A. Jones, A. Chalamet, J.L. Charpenteau, and J.R. Marty. 1991. "Simulation of Soybean Nitrogen Nutrition for a Silty Clay Soil in Southern France." *Field Crops Res.* 26(1): 19-34.

Brown, R.A. and N.J. Rosenberg. 1997. "Sensitivity of Crop Yield and Water Use to Change in a Range of Climatic Factors and CO_2 Concentrations: A Simulation Study Applying EPIC to the Central USA." *Agric. Forest Meteor.* 83: 171-203.

———. 1999. "Climate Change Impacts on the Potential Productivity of Corn and Winter Wheat in their Primary United States Growing Regions. *Climatic Change* 41(1): 73-107.

Brown, R.A., N.J. Rosenberg, C.J. Hays, W.E. Easterling, and L.O. Mearns. 2000. "Potential Production and Environmental Effects of Switchgrass and Traditional Crops under Current and Greenhouse-Altered Climate in the Central United States: A Simulation Study." *Agric. Ecosyst. Environ.* 78: 31-47.

Bryant, K.J., J.D. Atwood, R.D. Lacewell, V.D. Lansford, B.A. McCarl, and P.T. Dyke. 1993. "Farm Level Impacts of the Coastal Zone Management Act Proposed Erosion Regulations." *J. Soil Water Cons.* 48(5): 466-70.

Bryant, K.J., V.W. Benson, J.R. Kiniry, J.R. Williams, and R.D. Lacewell. 1992. "Simulating Corn Yield Response to Irrigation Timings: Validation of the EPIC Model." *J. Prod. Agric.* 5: 237-42.

Cabelguenne, M., and P. Debaeke. 1998. "Experimental Determination and Modelling of the Soil Water Extraction Capacities of Crops of Maize, Sunflower, Soya Bean, Sorghum, and Wheat." *Plant and Soil* 202(2): 175-92.

Cabelguenne, M., P. Debaeke, and A. Bouniols. 1999. "EPICphase, A Version of the EPIC Model Simulating the Effects of Water and Nitrogen Stress on Biomass and Yield, Taking Account of Developmental Stages: Validation on Maize, Sunflower, Sorghum, Soybean, and Winter Wheat." *Agric. Syst.* 60(3): 175-96.

Cabelguenne, M., P. Debaeke, J. Puech, and N. Bosc. 1997. "Real Time Irrigation Management Using the EPIC-PHASE Model and Weather Forecasts." *Agric. Water Manage.* 32: 227-38.

Cabelguenne, M., C.A. Jones, J.R. Marty, P.T. Dyke, and J.R. Williams. 1990. "Calibration and Validation of EPIC for Crop Rotations in Southern France." *Agric. Syst.* 33(2): 153-71.

Cabelguenne, M., C.A. Jones, and J.R. Williams. 1995. "Strategies for Limited Irrigations of Maize in Southwestern France—A Modeling Approach." *Trans. ASAE* 38(2): 507-11.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. "Organic C Accumulation in Soil Over 30 Years in Semiarid Southwestern Saskatchewan—Effect of Crop Rotations and Fertilizers." *Can. J. Soil Sci* 80: 179-92.

Cavero, J., I. Farre, P. Debaeke, and J.M. Faci. 2000. "Simulation of Maize Yield under Water Stress with the EPICphase and CROPWAT Models." *Agron. J.* 92: 679-90.

Cavero, J., R.E. Plant, C. Shennan, D.B. Friedman, J.R. Williams, J.R. Kiniry, and V.W. Benson. 1999. "Modeling Nitrogen Cycling in Tomato-Safflower and Tomato-Wheat Rotations." *Agric. Syst.* 60: 123-35.

Cavero, J., R.E. Plant, C. Shennan, J.R. Williams, J.R. Kiniry, and V.W. Benson. 1997. "Application of EPIC Model to Nitrogen Cycling in Irrigated Processing Tomatoes under Different Management Systems." *Agric. Syst.* 60: 123-35.

———. 1998. "Application of EPIC Model to Nitrogen Cycling in Irrigated Processing Tomatoes under Different Management Systems." *Agric. Syst.* 56(4): 391-414.

Cavero, J., E. Playán, N. Zapata, and J.M. Faci. 2001. "Simulation of Maize Grain Yield Variability within a Surface-Irrigated Field." *Agron. J.* 93: 773-82.

Chang, C.C., J.D. Atwood, K. Alt, and B.A. McCarl. 1994. "Economic Impacts of Erosion Management Measures in Coastal Drainage Basins." *J. Soil Water Cons.* 49(6): 606-11.

Chen, X., W.L. Harman, M. Magre, E. Wang, R. Srinivasan, and J.R. Williams. 2000. "Water Quality Assessment with Agro-Environmental Indexing of Non-Point Sources, Trinity River Basin." *Trans. ASAE 16*(4): 405-17.

Chowdhury, M.E., and R.D. Lacewell. 1996. "Implications of Alternative Policies on Nitrate Contamination of Groundwater." *J. Agric. Resour. Econ. Assoc.* 21(1): 82-95.

Chung, S.W., P.W. Gassman, R. Gu, and R.S. Kanwar. 2002. "Evaluation of EPIC for Assessing Tile Flow and Nitrogen Losses for Alternative Agricultural Management Systems." *Trans. ASAE* 45(4): 1135-46.

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

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): 971-99.

Coiner, C., J. Wu, and S. Polasky. 2001. "Economic and Environmental Implications of Alternative Landscape Designs in the Walnut Creek Watershed of Iowa." *Ecol. Econ.* 38: 119-39.

Cooter, E.J., and G.B. Dhakhwa. 1995. "A Solar Radiation Model for Use in Biological Applications in the South and Southwestern USA." *Agric. Forest Meteor.* 78: 31-51.

Debaeke, P. 1995. "Wheat Response to Supplementary Irrigation in South-Western France," pt. 2, "A Frequential Approach Using a Simulation Model." *Agric. Mediter.* 135: 64-78.

de Barros, I., J.R. Williams, and T. Gaiser. 2004. "Modeling Soil Nutrient Limitations to Crop Production in Semiarid NE of BRAZIL with a Modified EPIC Version I: Changes in the Source Code of the Model." *Ecol. Model.* 178: 441-56.

Deybe, D., and G. Flichman. 1991. "A Regional Agricultural Model Using a Plant Growth Simulation Program as Activities Generator—An Application to a Region in Argentina." *Agric. Syst.* 37: 369-85.

Dhakhwa, G.A., and C.L. Campbell. 1998. "Potential Effects of Differential Day-Night Warming in Global Climate Change on Crop Productions." *Climatic Change* 40: 647-67.

Dhakhwa, G.B., C.L. Campbell, S.K. LeDuc, and E.J. Cooter. 1997. "Maize Growth: Assessing the Effects of Global Warming and CO_2 Fertilization with Crop Models." *Agric. Forest Meteor.* 87: 253-72.

Díaz, R.A., G.O. Magrin, M.I. Travasso, and R.O. Rodríguez. 1997. "Climate Change and Its Impact on the Properties of Agricultural Soils in the Argentinean Rolling Pampas." *Climate Res.* 9(1-2): 25-30.

Easterling, W.E., X. Chen, C.J. Hays, J.R. Brandle, and H. Zhang. 1996. "Improving the Validation of Model-Simulated Crop Yield Response to Climate Change: An Application to the EPIC Model." *Climate Res.* 6: 263-73

Easterling, W.E., P.R. Crosson, N.J. Rosenberg, M.S. McKenney, and K.D. Frederick. 1992a. "Methodology for Assessing Regional Economic Impacts of and Responses to Climate Change: The MINK Study." In *Economic Issues in Global Climate Change: Agriculture, Forestry, and Natural Resources,* pp. 168-99. Edited by J.M. Reilly and M. Anderson. Boulder, CO: Westview Press.

Easterling, W.E., C.J. Hays, M.M. Easterling, and J.R. Brandle. 1997. "Modelling the Effect of Shelterbelts on Maize Productivity under Climate Change: An Application of the EPIC Model." *Agric. Ecosyst. Environ.* 61: 163-76.

Easterling, W.E, M.S. McKenney, N.J. Rosenberg, and K.M. Lemon. 1992b. "Simulations of Crop Responses to Climate Change: Effects with Present Technology and Currently Available Adjustments (the 'Dumb Farmer' Scenario)." *Agric. Forest Meteor.* 59(1-2): 75-102.

Easterling, W.E., L.O. Mearns, C.J. Hays, and D. Marx. 2001. "Comparison of Agricultural Impacts of Climate Change Calculated from High and Low Resolution Climate Change Scenarios," pt. 2, "Accounting for Adaptation and CO_2 Direct Effects." *Climatic Change* 51(2): 173-97.

Easterling, W.E., N.J. Rosenberg, K.M. Lemon, and M.S. McKenney. 1992c. "Simulations of Crop Responses to Climate Change: Effects with Present Technology and Currently Available Adjustments (the 'Smart Farmer' Scenario)." *Agric. Forest Meteor.* 59(1-2): 75-102.

Easterling, W.E., N.J. Rosenberg, M.S. McKenney, C.A. Jones, P.T. Dyke, and J.R. Williams. 1992d. "Preparing the Erosion Productivity Impact Calculator (EPIC) Model to Simulate Crop Response to Climate Change and the Direct Effects of CO_2." *Agric. Forest Meteor.* 59(1-2): 17-34.

Easterling, W.E., A. Weiss, C.J. Hays, and L.O. Mearns. 1998. "Spatial Scales of Climate Information for Simulating Wheat and Maize Productivity: The Case of the US Great Plains." *Agric. Forest Meteor.* 90: 51-63.

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.

Edwards, D.R., T.C. Daniel, and O. Marbun. 1992. "Determination of Best Timing for Poultry Waste Disposal: A Modeling Approach." *Water Resour. Bull.* 28(3): 487-94.

Ellis, J.R., R.D. Lacewell, J. Moore, and J.W. Richardson. 1993. "Preferred Irrigation Strategies in Light of Declining Government Support." *J. Prod. Agric.* 6(1): 112-11.

Engelke, R., and S. Fabrewitz. 1991. "Simulation Runs with the EPIC Model for Different Data Sets." In *Soil and Groundwater Report II: Nitrate in Soils*, pp. 288-99. Final Report. Luxembourg: Commission of the European Communities, Directorate-General, Telecommunications, Information Industries and Innovation.

Evers, AJ.M., R.L. Elliott, and E.W. Stevens. 1998. "Integrated Decision Making for Reservoir, Irrigation, and Crop Management." *Agric. Syst.* 58(4): 529-54.

Favis-Mortlock, D. 1998. "Validation of Field-Scale Soil Erosion Models using Common Datasets." In *Modelling Soil Erosion by Water,* pp. 89-127. Edited by J. Boardman and D. Favis-Mortlock. Berlin: Springer-Verlag.

Favis-Mortlock, D., and J. Boardman. 1995. "Nonlinear Responses of Soil Erosion to Climate Change: A Modelling Study on the UK South Downs." *Catena* 25: 365-87.

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.

Feng, H., L. Kurkalova, C.L. Kling, and P.W. Gassman. 2004. "Environmental Conservation in Agriculture: Land Retirement versus Changing Practices on Working Land." CARD Working Paper 04-WP 365. Center for Agricultural and Rural Development, Iowa State University. June. Submitted for publication.

Flowers, J., N. Easterling, and L. Hauck. 1998. "Prediction of Effects of Best Management Practices on Agricultural Nonpoint Source Pollution in the Arroyo Colorado Watershed." Project Report PR 97-06. Texas Institute for Applied Environmental Research, Tarleton State University.

Flowers, J.D., J.R. Williams, and L.M. Hauck. 1996. "NPP Integrated Modeling System: Calibration of the APEX Model for Dairy Waste Application Fields in Erath County, Texas." Project Report PR 96-07. Texas Institute for Applied Environmental Research, Tarleton State University.

Foltz, J.C., J.G. Lee, and M.A. Martin. 1993. "Farm-Level Economic and Environmental Impacts of Eastern Corn Belt Cropping Systems." *J. Prod. Agric.* 6: 290-96.

Foltz, J.C., J.G. Lee, M.A. Martin, and P.V. Preckel. 1995. "Multiattribute Assessment of Alternative Cropping Systems." *Amer. J. Agric. Econ.* 77: 408-20.

Forster, D.L. 2002. "Effects of Conservation Tillage on the Performance of Lake Erie Basin Farms." *J. Environ. Qual.* 31: 32-37.

Forster, D.L., R.P. Richards, D.B. Baker, and E.N. Blue. 2000. "EPIC Modeling of the Effects of Farming Practice Changes on Water Quality in Two Lake Erie Watersheds." *J. Soil Water Cons.* 55(1): 85-90.

Gaiser, T., M. Mounkaila, T. Maurer, and L. Herrman. 2003. "A Land Resource Database for the Republic of Niger to Estimate Topsoil Losses through Wind Erosion at the Regional Scale. In *Proceedings of Deustcher Tropentag 2003 Annual Conference*. Göttingen, Germany: Tropentag. http://www.tropentag.de/2003/ abstracts/full/310.pdf (accessed July 17 2004).

Gassman, P.W. 1997. "The National Pilot Program Integrated Modeling System: Environmental Baseline Assumptions and Results for the APEX Model (Livestock Series Report 9)." CARD Staff Report 97-SR 85. Center for Agricultural and Rural Development, Iowa State University.

Gassman, P.W., J. Abraham, L. Hauck, A. Saleh, and K. Keplinger. 2001. "Simulation of Nutrient Losses from Chicken Litter Applications in East Central Texas with APEX and SWAT." ASAE Paper No. 01-2004. American Society of Agricultural Engineers, St. Joseph, MI.

Gassman, P.W., T. Campbell, C. Izaurralde, A. M. Thomson, and J.D. Atwood. 2003a. "Regional Estimation of Soil Carbon and Other Environmental Indicators Using EPIC and i_EPIC." CARD Technical Report 03-TR 46. Center for Agricultural and Rural Development, Iowa State University. http://www.card.iastate.edu/publications/DBS/PDFFiles/03tr46.pdf (accessed July 17, 2004).

Gassman, P.W., E. Osei, A. Saleh, and L.M. Hauck. 2002. "Application of an Environmental and Economic Modeling System for Watershed Assessments." *J. Amer. Water Res. Assoc.* 38(2): 423-38.

Gassman, P.W., A. Saleh, E. Osei, J. Abraham, and J. Rodecap. 2003b. "Environmental and Economic Impacts of Alternative Management Systems for the Mineral Creek Watershed." In *Proceedings of the Total Maximum Daily Load (TMDL) Environmental Regulations Conference*, pp. 323-331. Edited by A. Saleh. ASAE Publication No. 701P0102. St. Joseph, MI: American Society of Agricultural Engineers.

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),* pp. 115-22. London: International Association on Water Quality.

Geleta, S., G.J. Sabbagh, J.F. Stone, R.L. Elliot, H.P. Mapp, D.J. Bernardo, and K.B. Watkins. 1994. "Importance of Soil and Cropping Systems in the Development of Regional Water Quality Policies." *J. Environ. Qual.* 23: 36-42.

Gray, A.W., W.L. Harman, J.W. Richardson, A.F. Weise, G.C. Regier, P.T. Zimmel, and V.D. Lansford. 1997. "Economic and Financial Viability of Residue Management: An Application to the Texas High Plains." *J. Prod. Agric.* 10: 175-83.

Harman, W.L., E. Wang, and J.R. Williams. 2004. "Reducing Atrazine Losses: Water Quality Implications of Alternative Runoff Control Practices." *J. Environ. Qual.* 33: 7-12.

Hayes, S.E., and J.D. Wingard. 2002. "Landscape and History: Social and Economic Change in Two Maya Valleys." Presented at the 2004 annual meeting of the Society for American Archeology, March 20-24, Denver, CO. http://www.sonoma.edu/users/p/poe /hist485/SAA2002_Hayes_Wingard.pdf (accessed June 2005).

Host, G.E., J.G. Isebrands, G.W. Theseira, J.R. Kiniry, and R.L. Graham. 1996. "Temporal and Spatial Scaling from Individual Trees to Plantations: A Modeling Strategy." *Biomass and Bioenergy* 11(2-3): 233-43.

Hughes, D., W. Butcher, A. Jaradat, and W. Penaranda. 1995. "Economic Analysis of the Long-Term Consequences of Farming Practices in the Barley Cropping Area of Jordan." *Agric. Syst.* 47: 39-58.

Huzár, T., J. Mika, D. Lóczy, K. Molnár, and Á Kertész. 1999. "Climate Change and Soil Moisture: A Case Study." *Phys. Chem. Earth* (A) 24(10): 905-12.

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 Modeling 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. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Izaurralde, R.C., N.J. Rosenberg, R.A. Brown, D.M. Legler, M. Tiscareño López, and R. Srinivasan. 1999. "Modeled Effects of Moderate and Strong 'Los Niños' on Crop Productivity in North America." *Agric. Forest Meteor.* 94: 259-68.

Izaurralde, R.C., N.J. Rosenberg, R.A. Brown, and A.M. Thomson. 2003. "Integrated Assessment of Hadley Center (HaDCM2) Climate-Change Impacts on Agricultural Productivity and Irrigation Water Supply in the Conterminous United States," pt. 2, "Regional Agricultural Production in 2030 and 2095." *Agric. Forest Meteorol*. 117(1-2): 97-122.

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, May 14-17, Washington, DC. http://www.netl.doe. gov/publications /proceedings /01/carbon_seq/5c2.pdf (accessed June 15, 2004).

———. 2004. "Modeling Soil Organic Carbon Changes in CRP Land and a Long Term Crop Rotation Trial with EPIC." Joint Global Change Research Institute, University of Maryland. Submitted for publication.

Jackson, L.E., L.J. Stivers, B.T. Warden, and K.K. Tanji. 1994. "Crop Nitrogen Utilization and Soil Nitrate Loss in a Lettuce Field." *Fert. Res.* 37: 93-105.

Jain, S.K., and F. Dolezal. 2000. "Modeling Soil Erosion using EPIC Supported by GIS, Bohemia, Czech Republic." *J. Environ. Hydrol.* 8(paper 2): 1-11. http://www.hydroweb.com (accessed July 17, 2004).

Jones, C.A., P.T. Dyke, J.R. Williams, J.R. Kiniry, V.W. Benson, and R.H. Griggs. 1991. "EPIC: An Operational Model for Evaluation of Agricultural Sustainability." *Agric. Syst.* 37: 341-50.

Jones, C.A., M.K. Wegner, J.S. Russell, I.M. McLeod, and J.R. Williams. 1989. "AUSCANE—Simulation of Australian Sugarcane with EPIC." Commonwealth Scientific and Industrial Research Organization, Brisbane, Australia.

Keith, G., S. Norvell, R. Jones, C. Maguire, E. Osei, A. Saleh, P. Gassman, and J. Rodecap. 2000. "Livestock and the Environment: A National Pilot Project: CEEOT-LP Modeling for the Upper Maquoketa River Watershed, Iowa: Final Report." Report No. PR0003. Texas Institute for Applied Environmental Research, Tarleton State University.

Kelly, T.C., Y. Lu, and J. Teasdale. 1996. "Economic-Environmental Tradeoffs among Alternative Crop Rotations." *Agric. Ecosyst. Environ.* 60: 17-28.

King, K.W., C.W. Richardson, and J.R. Williams. 1996. "Simulation of Sediment and Nitrate Loss on a Vertisol with Conservation Tillage Practices." *Trans. ASAE* 39(6): 2139-45.

Kiniry, J.R., R. Blanchet, J.R. Williams, V. Texier, C.A. Jones, and M. Cabelguenne. 1992a. "Sunflower Simulation using the EPIC and ALMANAC Models." *Field Crops Res.* 30(3-4): 403-23.

Kiniry, J.R., D.J. Major, R.C. Izaurralde, J.R. Williams, P.W. Gassman, M. Morrison, R. Bergentine, and R.P. Zentner. 1995. "EPIC Model Parameters for Cereal, Oilseed, and Forage Crops in the Northern Great Plains Region." *Can. J. Plant Sci.* 75(3): 679-88.

Kiniry, J.R., J.R. Williams, P.W. Gassman, and P. Debaeke. 1992b. "A General, Process-Oriented Model for Two Competing Plant Species." *Trans. ASAE* 35(3): 801-10.

Kling, C.L., H. Feng, L.A. Kurkalova, S. Secchi, P.W. Gassman, M. Jha, T. Campbell, A. Bhaskar, C. Burkart, S. Sengupta, and R. Olson. 2004. "Policies to Improve Water Quality: In-Stream versus Edge-of-Field Assessment. Selected poster presented at the American Agricultural Economics Association 2004 annual meeting, Denver, CO. http://www.card.iastate.edu/environment/ (accessed October 1, 2004).

Kurkalova, L., C.L. Kling, and J. Zhao. 2004. "Multiple Benefits of Carbon-Friendly Agricultural Practices: Empirical Assessment of Conservation Tillage." *Environ. Manage.* 33(4): 519-27.

Lakshminarayan, P.G, J.D. Atwood, S.R. Johnson, and V.A. Sposito. 1991. "Compromise Solution for Economic-Environmental Decisions in Agriculture." *J. Environ. Manage.* 33: 51-64.

Lakshminarayan, P.G., and B.A. Babcock. 1996. "Temporal and Spatial Evaluation of Soil Conservation Policies." CARD Working Paper 96-WP 149. Center for Agricultural and Rural Development, Iowa State University. http://www.card.iastate.edu/publications/DBS/PDFFiles/96wp149.pdf (accessed July 22, 2004).

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: 277-94.

Lal, R., J.M. Kimble, R.F. Follet, and C.V. Cole. 1998. "The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect." Ann Arbor, MI: Sleeping Bear Press.

Lee, J.J., D.L. Phillips, and R. Liu. 1993. "The Effect of Trends in Tillage Practices on Erosion and Carbon Content of Soils in the U.S. Corn Belt." *Water Air Soil Poll.* 70: 389-401.

Lee, J. J., D.L. Phillips, and V.W. Benson. 1999. "Soil Erosion and Climate Change: Assessing Potential Impacts and Adaptation Practices." *J. Soil Water Cons.* 54(3): 529-36.

Lee, J.J., D.L. Phillips, and R.F. Dodson. 1996. "Sensitivity of the US Corn Belt to Climate Change and Elevated CO_2," pt 2, "Soil Erosion and Organic Carbon." *Agric. Syst.* 52: 503-21.

Legler, D.M., K.J. Bryant, and J.J. O'Brien. 1999. "Impact of ENSO-Related Climate Anomalies on Crop Yields in the U.S." *Climatic Change* 42: 351-75.

Lunn, R.J., R. Adams, R. Mackay, and S.M. Dunn. 1996. "Development and Application of a Nitrogen Modelling System for Large Catchments." *J. Hydrol.* 174: 285-304

Martin, S.M., M.A. Nearing, and R.R. Bruce. 1993. "An Evaluation of the EPIC Model for Soybeans Grown in Southern Piedmont Soils." *Trans. ASAE* 36(5): 1327-31.

Mckenney, M.S., W.E. Easterling, and N.J. Rosenberg. 1992. "Simulation of Crop Productivity and Responses to Climate Change in the Year 2030: The Role of Future Technologies, Adjustments, and Adaptions." *Agric. Forest Meteor.* 59(1-2): 103-27.

McNitt, J., R. Jones, E. Osei, L. Hauck, and H. Jones. 1999. "Livestock and the Environment: Precedents for Runoff Policy; Policy Option-CEEOT-LP." Project Report PR9909. Texas Institute for Applied Environmental Research, Tarleton State University.

Mearns, L. O., W. Easterling, C. Hays, and D. Marx. 2001. "Comparison of Agricultural Impacts of Climate Change Calculated from High and Low Resolution Climate Change Scenarios," pt 1, "The Uncertainty Due to Spatial Scale." *Climatic Change* 51(2): 131-72.

Mearns, L.O., T. Mavromatis, E. Tsvetsinskaya, C. Hays, and W. Easterling. 1999. "Comparative Response of EPIC and CERES Crop Models to High and Low Resolution Climate Change Scenarios." *J. Geophys. Res.* 104: 6623-46.

Meza, F.J., and D.S. Wilks. 2004. Use of Seasonal Forecasts of Sea Surface Temperature Anomalies for Potato Fertilization Management: Theoretical Study Considering EPIC Model Results at Valdivia, Chile." *Agric. Syst.* 82(2): 161-80.

Michels, K., K.N. Potter, and J.R. Williams. 1997. "Simulation of Wind Erosion Damage to Pearl Millet in West Africa using EPIC." In *Proceedings Wind Erosion – An International Symposium/Workshop*. Edited by E. Skidmore and J. Tatarko. Manhattan, KS: U.S. Department of Agriculture, Agricultural Research Service Wind Erosion Research Unit, Kansas State University. http://www.weru.ksu.edu/symposium/proceedings/michels.pdf (accessed July 17, 2004).

Mimouni, M., S. Zekri, and G. Flichman. 2000. "Modelling the Trade-Offs between Farm Income and the Reduction of Erosion and Nitrate Pollution." *Annals Oper. Res.* 94(1-4): 91-103.

Mitchell, P.D., P.G. Lakshminarayan, T. Otake, and B.A. Babcock. 1998. "The Impact of Soil Conservation Policies on Carbon Sequestration in Agricultural Soils of the Central United States." In *Management of Carbon Sequestration in Soil,* pp. 125-42. Edited by R. Lal, J.M. Kimble, R.F. Follett, and B.A. Stewart. Boca Raton, FL: CRC Press.

Moulin, A.P. and H.J. Beckie. 1993. "Evaluation of the CERES and EPIC Models for Predicting Spring Wheat Grain Yield over Time." *Can. J. Plant Sci.* 73(3): 713-719.

Osei, E., B. Du, A. Bekele, L. Hauck, A. Saleh, and A. Tanter. 2004. "CEEOT-MMS: A Macro Modeling System for Environmental Assessment—Application to Texas Animal Feeding Operations." Texas Institute for Applied Environmental Research, Tarleton State University.

Osei, E., P.W. Gassman, L.M. Hauck, R. Jones, L. Beran, P.T. Dyke, D.W. Goss, J.D. Flowers, and A.M.S. McFarland. 2003a. "Economic Costs and Environmental Benefits of Manure Incorporation on Dairy Waste Application Fields. *J. Environ. Manage.* 68(1): 1-11.

Osei, E., P.W. Gassman, L.M. Hauck, S. Neitsch, R.D. Jones, J. Mcnitt, and H. Jones. 2003b. "Using Nutrient Management to Control Nutrient Losses from Dairy Pastures." *J. Range Manage.* 56: 218-26.

Osei, E., P.W. Gassman, R. Jones, S. Pratt, L. Hauck, L. Beran, W. Rosenthal, and J.R. Williams. 2000. "Economic and Environmental Impacts of Alternative Practices on Dairy Farms in an Agricultural Watershed." *J. Soil Water Cons.* 55(4): 466-72.

Osei, E., P. Gassman, and A. Saleh. 2000. "Livestock and the Environment: A National Pilot Project; Economic and Environmental Modeling Using CEEOT." Project Report PR0002. Texas Institute for Applied Environmental Research, Tarleton State University.

Parsons, R.L., J.W. Pease, and D.C. Martens. 1995. "Simulating Corn Yields over 16 Years on Three Soils under Inorganic Fertilizer and Hog Manure Fertility Regimes." *Commun. Soil Sci. Plant Anal.* 26(7-8): 1133-50.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel. 1994. "A General Model for Soil Organic Matter Dynamics: Senstivity to Litter Chemistry, Texture and Management. In *Quantitative Modeling of Soil Forming Processes*, pp. 147-67. SSSA Spec. Public. No. 39. Madison, WI: Soil Science Society of America.

Pautsch, G.R., L.A. Kurkalova, B.A. Babcock, and C.L. Kling. 2001. "The Efficiency of Sequestering Carbon in Agricultural Soils." *Cont. Econ. Policy* 19(2): 123-134.

Perez-Quezada, J.F., J. Cavero, J. Williams, A. Roel, and R.E. Plant. 2003. "Simulation of Within-Field Yield Variability in a Four-Crop Rotation Field using SURRGO Soil-Unit Definitions and the EPIC Model. *Trans. ASAE* 46(5): 1365-74.

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 Water Cons.* 48(5): 449-57.

Phillips, D.L., J.J. Lee, and R.F. Dodson. 1996. "Sensitivity of the US Corn Belt to Climate Change and Elevated CO_2: I. Corn and Soybean Yields." *Agric. Syst.* 52(4): 481-502.

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, P.D. Schroeder, D.E. Radcliffe, H.A. Kuykendall, V.W. Benson, J.R. Williams, C.S. Hoveland, and M.A. McCann. 2001. "Phosphorus Losses from Grasslands Fertilized with Broiler Litter: EPIC Simulations." *J. Environ. Qual.* 30: 1790-95.

Potter, K.N. and J.R. Williams. 1994. "Predicting Daily Mean Temperatures in the EPIC Simulation Model. *Agron. J*. 86(6):1006-11.

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.

Potter, S.R., J.D. Atwood, and D.W. Goss. 2001. "Modeling Regional and National Non-Point Source Impacts from US Agriculture." ASAE Paper No. 01-2191. American Society of Agricultural Engineers, St Joseph, MI.

Potter, S.R., J.D. Atwood, R. L. Kellogg, and J.R. Williams. 2004. "An Approach for Estimating Soil Carbon using the National Nutrient Loss Database." *Environ. Manage.* 33(4): 496-506.

Poudel, D.D., D.J. Midmore, and L.T. West. 2000. "Farmer Participatory Research to Minimize Soil Erosion on Steepland Vegetable Systems in the Philippines." *Agric. Ecosyst. Environ.* 79: 113-27.

Pratt, S., R. Jones, and C.A. Jones. 1997. "Livestock and the Environment: Expanding the Focus: Policy Options: CEEOT-LP." Project Report PR 96-03. Texas Institute for Applied Environmental Research, Tarleton State University

Priya, S., and R. Shibasaki. 2001. "National Spatial Crop Yield Simulation using GIS-Based Crop Production Model." *Ecol. Model.* 135: 113-29.

Purveen, H., R.C. Izaurralde, D.S. Chanasyk, J.R. Williams, and R.F. Grant. 1997. "Evaluation of EPIC's Snowmelt and Water Erosion Submodels using data from the Peace River Region of Alberta." *Can. J. Soil Sci.* 77: 41-50.

Putnam, J., J. Williams, and D. Sawyer. 1988. "Using the Erosion-Productivity Impact Calculator (EPIC) to Estimate the Impact of Soil Erosion for the 1985 RCA Appraisal." *J. Soil Water Cons*. 43(4): 321-26.

Quinones, H., and M. Cabelguenne. 1990. "Use of EPIC to Study Cropping Systems," pt. 2, "Improved Simulation of the Water Use, Growth, and Harvest Index in Corn." *Agric. Mediter.* 120: 241-48.

Ramanarayanan, T.S., J.R. Williams, W.A. Dugas, L.M. Hauck, and A.M.S. McFarland. 1997. "Using APEX to Identify Alternative Practices for Animal Waste Management." ASAE Paper 97-2209. American Society of Agricultural Engineers, St. Joseph, MI.

Rao, M.N., D.A. Waits, and M.L. Neilsen. 2000. "A GIS-Based Modeling Approach for Implementation of Sustainable Farm Management Practices." *Environ. Model. Software* 15(8): 745-53.

Rejesus, R.M., and R.H. Hornbaker. 1999. "Economic and Environmental Evaluation of Alternative Pollution-Reducing Nitrogen Management Practices in Central Illinois." *Agric. Ecosyst. Environ.* 75: 41-53.

Renard, K.G. 1997. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Loss Soil Equation (RUSLE).* Washington, DC: U.S. Department of Agriculture, Agricultural Research Service.

Reyes, M.R., C.W. Raczkowski, G.A. Gayle, and G.B. Reddy. 2004. "Comparing the Soil Loss Predictions of GLEAMS, RUSLE, EPIC, and WEPP." *Trans. ASAE* 47(2): 489-93.

Richter, J., and D.K. Benbi. 1996. "Modeling of Nitrogen Transformations and Translocations." *Plant Soil* 181: 109-21.

Rinaldi, M. 2001. "Application of EPIC Model for Irrigation Scheduling of Sunflower in Southern Italy." *Agric. Water Manage.* 49: 185-96.

Roloff, G., R. de Jong, and M.C. Nolin. 1998a. "Crop Yield, Soil Temperature and Sensitivity of EPIC under Central-Eastern Canadian Conditions." *Can. J. Plant Sci.* 78(3): 431-39.

———. 1998b. "EPIC Estimates of Soil Water, Nitrogen and Carbon under Semiarid Temperate Conditions." *Can. J. Plant Sci.* 78(3): 551-62.

Roloff, G., R. de Jong, R.P. Zentner, C.A. Campbell, and V.W. Benson. 1998. "Estimating Spring Wheat Yield Variability with EPIC." *Can. J. Plant Sci.* 78(3): 541-49.

Rosenberg, N.J., M.S. McKenney, W.E. Easterling, and K.M. Lemon. 1992. "Validation of EPIC Model Simulations of Crop Responses to Current Climate and CO_2 Conditions: Comparisons with Census, Expert Judgement and Experimental Plot Data." *Agric. Forest Meteor.* 59(1-2): 35-51.

Sabbagh, G.J., R.L. Bengston, and J.L. Fouss. 1991. "Modification of EPIC to Incorporate Drainage Systems." *Trans. ASAE* 34(2): 467-71.

Sabbagh, G. J., J.L. Fouss, and R.L. Bengston. 1993. "Comparison of EPIC-WT and DRAINMOD Simulated Performance of Land Drainage Systems." *Trans. ASAE* 36: 73-79.

Sabbagh, G.J., S. Geleta, R.L. Elliott, J.R. Williams, and R.H. Griggs. 1991. "Modification of EPIC to Simulate Pesticide Activities: EPIC-PST." *Trans. ASAE* 34(4): 1683-92.

Sabbagh, G.J., P.E. Norris, S. Geleta, D.J. Bernado, R.L. Elliott, H.P. Mapp, and J.F. Stone. 1992. "Environmental and Economic Impacts of Pesticide and Irrigation Practices: EPIC-PST Simulation." *J. Prod. Agric.* 5: 312-17.

Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland. 2000. "Application of SWAT for the Upper North Bosque River Watershed." *Trans. ASAE* 43(5): 1077-87.

Saleh, A. J.R. Williams, J.C. Wood, L.M. Hauck, and W.H. Blackburn. 2004. "Application of APEX for forestry." *Trans. ASAE* 47(3): 751-65.

Santos, A.M., M. Cabelguenne, F.L. Santos, M.R. Oliveira, and R.P. Serralheiro. 2000. "EPIC-PHASE: A Model to Explore Irrigation Strategies." *J. Agric. Engr. Res.* 75(4): 409-16.

Savard, M. 2000. "Modelling Risk, Trade, Agricultural and Environmental Policies to Assess Trade-Offs between Water Quality and Welfare in the Hog Industry." *Ecol. Model.* 125: 51-66.

Schaub, D., S. Meier-Zielinski, and R. U. Goetz. 1998. "Simulating Long-Term Erosion Effects on Soil Productivity for Central Switzerland using the EPIC Model." In *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes.* Edited by W. Summer, E. Klaghofer, and W. Zhang. IAHS Publication No. 249. Wallingford, UK: International Association of Hydrological Sciences.

Schneider, S.H., W.E. Easterling, and L.O. Mearns. 2000. "Adaptation: Sensitivity to Natural Variability, Agent Assumptions, and Dynamic Climate Changes." *Climatic Change* 45: 203-21.

Shankar, B., E.A. DeVuyst, D.C. White, J.B. Braden, and R.H. Hornbaker. 2000. "Nitrate Abatement Practices, Farm Profits, and Lake Water Quality: A Central Illinois Case Study." *J. Soil Water Cons*. 55(3): 296-303.

Sharpley, A.N., and J.R. Williams, eds. 1990. *EPIC – Erosion/Productivity Impact Calculator: 1. Model Documentation.* Washington, DC: USDA Technical Bulletin No. 1768.

Steiner, J.L., J.R. Williams, and O.R. Jones. 1987. "Evaluation of the EPIC Simulation Model using a Dryland Wheat-Sorghum-Fallow Crop Rotation." *Agron. J.* 79(4): 732-38.

Stockle, C.O., P.T. Dyke, J.R. Williams, C.A. Jones, and N.J. Rosenberg. 1992a. "A Method for Estimating the Direct and Climatic Effects of Rising Atmospheric Carbon Dioxide on Growth and Yield of Crops. II. Sensitivity Analysis at Three Sites in the Midwestern USA." *Agric. Syst.* 38(3): 239-56.

Stockle, C.O., J.R. Williams, C.A. Jones, and N.J. Rosenberg. 1992b. "A Method for Estimating the Direct and Climatic Effects of Rising Atmospheric Carbon Dioxide on Growth and Yield of Crops. I. Modification of the EPIC Model for Climate Change Analysis." *Agric. Syst.* 38(3): 225-38.

Sugiharto, T., T.H. McIntosh, R.C. Uhrig, and J.J. Lardinois. 1994. "Modeling Alternatives to Reduce Dairy Farm and Watershed Nonpoint Source Pollution." *J. Environ. Qual.* 23: 18-24.

Tan, G., and R. Shibasaki. 2003. "Global Estimation of Crop Productivity and the Impacts of Global Warming by GIS and EPIC Integration." *Ecol. Model.* 168: 357-70.

Tayfur, G., K.K. Tanji, B. House, F. Robinson, L. Teuber, and G. Kruse. 1995. "Modeling Deficit Irrigation in Alfalfa Production." *J. Irrig. Drain. Engr.* 121(6): 442-51.

Taylor, M.L., R.M. Adams, and S.F. Miller. 1992. "Farm-Level Response to Agricultural Effluent Control Strategies: The Case of the Willamette Valley." *J. Agric. Resour. Econ.* 17(1): 173-83.

Teague, M.L., D.J. Bernardo, and H.P. Mapp. 1995. "Meeting Environmental Goals Efficiently on a Farm-Level Basis." *Rev. Agric. Econ.* 17: 37-50.

Texier, V., R. Blanchet, and A. Bouniols. 1992. "Influence of Pluriannual Weather Conditions on Parameters of Sunflower Growth Modeling in Southwestern France." In Proceedings of the 13th International Sunflower Conference. Pisa, Italy: IFEVA [Agricultural Plant Physiology and Ecology Research Institute].

Thomson, A.M., R.A. Brown, and S.J. Ghan. 2002. "Elevation Dependence of Winter Wheat Production in Eastern Washington State with Climate Change: A Methodological Study." *Climatic Change* 54(1-2): 141-64.

Thomson, A.M., R.C. Izaurralde, and N.J. Rosenberg. 2002. "Modeling Agricultural Soil C Sequestration on Global Scales." *Agron. Abs.* p. 154.

Touré, A., D.J. Major, and C.W. Lindwall. 1994. "Comparison of Five Wheat Simulation Models in Southern Alberta." *Can. J. Plant Sci.* 75(1): 61-68.

———. 1995. "Sensitivity of Four Wheat Simulation Models to Climate Change." *Can. J. Plant Sci.* 75(1): 61-68.

Tumas, R. 2000. "Evaluation and Prediction of Nonpoint Pollution in Lithuania." *Ecol. Engr.* 14(4): 443-51.

Van Pelt, R.S., T.M. Zobeck, K.N. Potter, J.E. Stout, and T.W. Popham. 2004. "Validation of the Wind Erosion Stochastic Simulator (WESS) and the Revised Wind Erosion Equation (RWEQ) for Single Events." *Environ. Model. Software* 19(2): 191-98.

Vandyke, L.S., J.W. Pease, D.J. Bosch, and J.C. Baker. 1999. "Nutrient Management Planning on Four Virginia Farms: Impacts on Net Income and Nutrient Losses." *J. Soil Water Cons.* 54(2): 499-505.

Ventrella, D., and M. Rinaldi. 1999. "Comparison between Two Simulation Models to Evaluate Cropping Systems in Southern Italy: Yield Response and Soil Water Dynamics." *Agric. Mediter.* 129: 99-110.

Wang, E., W.L. Harman, J.R. Williams, and C. Xu. 2002. "Simulated Effects of Crop Rotations and Residue Management on Wind Erosion in Wuchuan, West-Central Inner Mongolia, China." *J. Environ. Qual.* 31: 1240-47.

Warner, G.S., J.D. Stake, K. Guillard, and J. Neafsey. 1997a. "Evaluation of EPIC for a Shallow New England Soil: I. Maize Yield and Nitrogen Uptake." *Trans. ASAE* 40(3): 575-83.

———. 1997b. "Evaluation of EPIC for a Shallow New England Soil: II. Soil Nitrate." *Trans. ASAE* 40(3): 585-93.

Weiss, A., C.J. Hays, Q. Hu, and W.E. Easterling. 2001. "Incorporating Bias Error in Calculating Solar Irradiance: Implications for Crop Yield Simulations." *Agron. J.* 93: 1321-26.

West, T.O., and W.M. Post. 2002. "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis." *Soil Sci. Soc. Amer. J.* 66: 1930-46.

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,* pp 909-1000. Edited by V.P. Singh. Highlands Ranch, CO: Water Resources Publications.

———. 2002. "The APEX Manure Management Component. In *Proceedings of the Total Maximum Daily Load (TMDL) Environmental Regulations Conf.*, pp. 44-51. Edited by A. Saleh. ASAE Publication No. 701P0102. St. Joseph, MI: American Society of Agricultural Engineers.

Williams, J.R., J.G. Arnold, and R. Srinivasan. 2000. "The APEX Model." BRC Report No. 00-06. Texas Agric. Expt. Station, Texas Agric. Exten. Service, Texas A&M University.

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.A. Jones, P.W. Gassman, and L.M. Hauck. 1995. "Simulation of Animal Waste Management with APEX." In *Innovations and New Horizons in Livestock and Poultry Manure Management*, pp. 22-26. College Station, TX: Texas A&M University.

Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel. 1989. "The EPIC Crop Growth Model." *Trans. ASAE* 32(2): 497-511.

Williams, J., M. Nearing, A. Nicks, E. Skidmore, C. Valentin, K. King, and R. Savabi. 1996. "Using Soil Erosion Models for Global Change Studies." *J. Soil and Water Cons.* 51(5): 381-85.

Williams, J.R., T.S. Ramanarayanan, W.A. Dugas, L.M. Hauck, and A.M.S. McFarland. 1997. "Using APEX to Identify Alternative Practices for Animal Waste Management," pt. 2, "Alternative Management Analyses." Research Paper. Blackland Research and Extension Center, Texas A&M University.

Williams, J.R., K.G. Renard, and P.T. Dyke. 1983. "EPIC: A New Method for Assessing Erosion's Effect on Soil Productivity." *J. Soil and Water Cons.* 38(5): 381-83.

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.

Wingard, J.D. 1996. "Interactions between Demographic Processes and Soil Resources in the Copán Valley, Honduras." In *The Managed Mosaic: Ancient Maya Agriculture and Resource Use.* Edited by S.L. Fedick. Salt Lake City, UT: University of Utah Press.

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

Wu, J., M.L. Teague, H.P. Mapp, and D.J. Bernardo. 1995. "An Empirical Analysis of the Relative Efficiency of Policy Instruments to Reduce Nitrate Water Pollution in the U.S. Southern High Plains." *Can. J. Agric. Econ.* 43: 403-20.

Zhao, J., L.A. Kurkalova, and C.L. Kling. 2004. "Alternative Green Payment Policies when Multiple Benefits Matter." *Agric. Resour. Econ. Rev.* 33(1): 148-58