United States
Department
of Agriculture

Economic
Research
Service

Technical
Bulletin
Number 1916

March 2007

Regional Environment and Agriculture Programming Model

Robert Johansson, Mark Peters, and Robert House

USDA
United States Department of Agriculture

Technical Bulletin Number 1916

March 2007

A Report from the Economic Research Service

www.ers.usda.gov

Regional Environment and Agriculture Programming Model

Robert Johansson, Mark Peters, and Robert House

Abstract

This bulletin presents the Regional Environment and Agriculture Programming Model (REAP), which was formerly known as USMP (U.S. Mathematical Programming Regional Agriculture Sector Model). This bulletin is a reference document for analysts and model users. It includes an outline of the objectives of REAP, describes the methodology used to achieve these objectives, and provides details on how REAP works. This bulletin provides the theoretical and modeling system specification, descriptions of the data used, and a guide for setting up and running model simulations. REAP is designed for spatial analyses of U.S. agricultural and environmental policies. REAP has been applied to soil conservation and environmental policy design, water quality, environmental credit trading, irrigation policy, climate change mitigation policy, trade and the environment, livestock waste management, wetlands policy, new or alternative fuels from agriculture products, crop and animal disease, and regional effects of trade agreements.

Keywords: Agriculture, environment, policy, mathematical programming, agricultural sector model.

Acknowledgments

The model and this documentation have undergone numerous changes and innovations over its current lifespan, more than 20 years now. We thank the many researchers who provided their expertise in developing the potential of this simulation model. These researchers include Howard McDowell, Terry Hickenbotham, Terry Disney, Ralph Heimlich, Vince Breneman, Jonathan Kaplan, Paul Faeth, Mindy Selman, Jimmy Williams, and many others at the U.S. Department of Agriculture and the World Resources Institute. We would also like to acknowledge Marca Weinberg, Kitty Smith, and Mary Bohman, USDA, Economic Research Service, for providing administrative support throughout the development of this technical documentation project. We also thank David Abler, Agapi Somwaru, Kazim Konyar, and an anonymous reviewer who provided excellent suggestions and edits throughout this project. And finally, thanks to Sharon Lee and Wynnice Pointer-Napper, USDA, Economic Research Service for editorial and design assistance.

About the Authors

Robert Johansson is an economist at the U.S. Office of Management and Budget, and Mark Peters is an economist with the National Resources Conservation Service, U.S. Department of Agriculture (USDA); both were with the Economic Research Service, USDA, earlier. Robert House, an economist retired from the Economic Research Service, USDA, is an agricultural policy consultant with Environmental Defense. Contributors to this bulletin are Scott Malcolm, economist with the Economic Research Service, USDA, Suzie Greenhalgh and Elizabeth Marshall, economists with the World Resources Institute, and John Westra, an assistant professor of agricultural economics at the Louisiana State University, Agricultural Center.

Contact information:
Scott Malcolm, 202-694-5517, smalcolm@ers.usda.gov

Recommended citation format for this publication:

Johansson, Robert, Mark Peters, and Robert House. *Regional Environment and Agriculture Programming Model*, TB-1916. U.S. Dept. of Agriculture, Econ. Res. Serv. March 2007.

Contents

Summary

Development of the U.S. Mathematical Programming Regional Agricultural Sector Model (USMP) began in 1985 to augment economic and environmental policy analysis at the U.S. Department of Agriculture's Economic Research Service. Analysts needed a way to represent the interactions among product prices, choice of production practices, and demand for crop and livestock products when analyzing the potential effects of policies designed to address environmental issues associated with agriculture. The effects of environmental and energy policies were so widespread and the interaction among the various commodities so complex that it was impossible for analysts, using the available analytical tools and research results to project the ultimate effect of specified policies on agricultural producers or even to determine whether the policies would achieve their desired goals. This bulletin presents the current version of the USMP model—now the Regional Environment and Agriculture Programming Model (REAP)—its theoretical and modeling system specification, descriptions of the data used, and a guide for setting up and running model simulations.

What Are the Issues?

Many agricultural policy issues stem from agricultural production and its interface with the environment. Modeling efforts are important for informing policymakers on how these issues might influence the heterogeneous set of farms, farmers, and environmental resources that characterize U.S. agricultural production. Agricultural policy issues analyzed using REAP include soil conservation and environmental policy design, water quality, environmental credit trading, irrigation policy, climate change mitigation policy, trade and the environment, livestock waste management, wetlands policy, new or alternative fuels from agriculture products, crop and animal disease, and regional effects of trade agreements.

What Does the Model Do?

REAP is designed for general-purpose economic, environmental, technological, and policy analysis of the U.S. agriculture sector. REAP facilitates scenario—or "what if"—analyses by showing how changes in technology, commodity supply or demand, or farm, resource, environmental, or trade policy could affect a host of performance indicators important to decisionmakers and stakeholders. Analysts perform "what if" analyses by solving for a baseline, or status quo, economic equilibrium, then imposing specific policy, technology, trade, or other changes on the system and solving REAP again to compute a new economic equilibrium consistent with the scenario changes. Performance indicators include regional values for land use, input use, crop and animal production and prices, farm income, government expenditures, farm program participation, and environmental emissions such as erosion, nutrient and pesticide loadings, and greenhouse

gases. The scenarios analyzed do not predict a dated forecast or projection, but rather present the likely effect of proposed changes in policies, regulations, and markets on the agriculture sector's performance, holding constant all other conditions affecting the sector.

REAP is a price-endogenous mathematical programming model. As such, it incorporates the assumptions of neoclassical economics, supplemented by the best available estimated behavioral and biophysical relationships (e.g., for agricultural commodity supply and demand or nitrogen run off). Many regularly updated data sets—production practices surveys, multiyear baselines, macroeconomic trend projections, and regional resource and land databases—are applied to construct and update REAP. To generate a baseline scenario, disaggregated regional data are used to map the baseline data projections into REAP's smaller units of analysis. The relationships between production practices and environmental performance indicators represented in the model are derived by using biophysical models.

How Does the Model Work?

- REAP cropping enterprises, or activities that include rotation, tillage, and fertilizer choices, are linked to the Environmental Policy Integrated Climate Model (EPIC), a biophysical model of crop production. In addition to the effect of production practices on yields, EPIC is used to compute environmental indicators such as nitrogen loss and greenhouse gas emissions per acre for each REAP crop system, thereby augmenting economic analysis of "what if" scenarios with their environmental effects as well.

- Land use, crop mix, multiyear crop rotations, tillage practices, and nitrogen fertilizer application rates are all endogenously determined in REAP's 45 production regions. Scenario analysis explores the response of all these variables to "what if" changes in policy incentives, regulations, market conditions, technology, and so forth.

- Crop and livestock primary and secondary products are all integral parts of the model and interact in the solution process. Cattle, poultry, and swine feed rations are formed from activities that process crops into protein, energy, and trace elements necessary for the respective animal diets. Policy and market shocks that directly affect either the crop or livestock industry ultimately result in a market equilibrium that reflects the repercussions for agricultural industries and markets.

- REAP provides comparative static analysis from any base year in the historical/baseline data, which is approximately 1988-2015. REAP is typically calibrated to a current or future year selected from the 10-year USDA baseline. For example, REAP is to be calibrated to the 2010 baseline for scenario analysis of changes introduced in 2010. Near-term analyses of policy, market, or technology shocks reflect short- or medium-term sector responses; long-term analyses reflect longer run adjustments.

- The explicit linkages in REAP between production activities and environmental emissions indicators can be exploited to extend analysis to alternative environmental policy scenarios. For example, REAP was extended in 1999 to provide analysis of the effects of the Kyoto Protocol on U.S. agriculture. REAP has also been extended by the World Resources Institute to examine excess fertilizer nutrient (phosphorus) pollution in the Great Lakes, hypoxia, climate change, and point/nonpoint emissions trading.

- Data used are readily available. Most core model data are prepared and regularly updated by agencies of the U.S. Department of Agriculture. REAP applies USDA and ERS data and estimates to agriculture sector analysis. This includes ERS cost of production data, USDA acreage and production data, baseline data, and changes to commodity program policy instruments (e.g., fixed and counter-cyclical payments, target prices, loan rates, loan deficiency payments, and domestic agrienvironmental programs).

Introduction

This bulletin describes the Regional Environment and Agriculture Programming Model (REAP), which was formerly known as USMP, or the U.S. Mathematical Programming Regional Agriculture Sector Model (box 1). This bulletin is a reference document for analysts and model users.[1] In this bulletin, we outline the objectives of REAP, describe the methodology used to achieve these objectives and provide details on how REAP works.

Many agricultural policy issues stem from agricultural production and its interface with the environment. REAP is a powerful tool for analyzing the effects of policy on both agricultural structure and the environment. This model has been applied to:

- soil conservation and environmental policy design (Cattaneo et al., 2005; Claassen et al., 2001);
- water quality (Doering et al., 1998; Ribaudo et al., 2001; Peters et al., 1997; Greenhalgh and Faeth, 2001; Greenhalgh and Sauer, 2003);
- environmental credit trading (Ribaudo et al., 2005);
- irrigation policy (Horner et al., 1990);
- climate change mitigation policy (Peters et al., 2001; Faeth and Greenhalgh, 2000; Faeth and Greenhalgh, 2002; Lewandrowski et al., 2004);
- trade and the environment (Johansson et al., 2005; Cooper et al., 2005);
- livestock waste management (Ribaudo et al., 2003; Aillery et al., 2005; Johansson and Kaplan, 2004; Kaplan et al., 2004);
- wetlands policy
- new or alternative fuels from agriculture products (Marshall and Greenhalgh, 2006; House et al., 1993);
- crop and animal disease (Livingston et al., 2004; Disney and Peters, 2003); and
- regional effects of trade agreements (Burfisher et al., 1992).

REAP combines information on agricultural commodity supply and use relationships with policy instruments and environmental parameters. The model simulates how changes in government agricultural or environmental policy could result in changes to production practices and the effects of those changes on commodity markets, net returns, and the agriculture sector's environmental performance.

The model includes the major commodity crops, a number of livestock enterprises, and a variety of different processing technologies used to produce retail products from agricultural inputs. The data used to drive REAP are drawn from a number of national databases: the USDA production practices survey, the USDA multiyear baseline, and the National Resources Inventory.

REAP divides the United States into production regions, derived from the intersection of the USDA Farm Production Regions, Land Resource Regions, and soil erodibility classification. For each of those regions, land use, crop mix, multiyear crop rotations, tillage practices, and nitrogen fertilizer application rates are all endogenously determined by REAP's constrained optimization process. The biophysical effects of those rotations and tillage practices are then estimated by using a crop biophysical simulation model called the Environmental Policy Integrated Climate (EPIC) model.

[1] REAP retains basic historical policy mechanisms (i.e., no-longer-used government commodity or conservation programs which may be switched off or on) to facilitate analysis if a variant of an old program returns to current policy. However, completely rebasing REAP to the policy and market conditions of a historical year (e.g., for historical counterfactual analysis) might require substantial effort.

Changes in policy, demand, or production/processing technology can, therefore, be imposed upon the model and the results examined to determine their effects on the following:

- regional supply of crops and livestock;
- commodity prices;
- crop management behavior and use of production inputs;
- farm income; and
- environmental indicators such as nutrient and pesticide runoff, soil loss, greenhouse gas emissions, soil carbon fluxes, and energy use.

Due to the highly aggregated nature of the model and the coarseness of the estimation, REAP results are generally used to evaluate the relative effects of various policy options and not to predict absolute changes in production or environmental parameters.

Economic Modeling

The REAP model is a comparative-static, regional, mathematical programming model of U.S. agriculture. The model is written and maintained in GAMS (General Algebraic Modeling System). REAP seeks to determine the set of prices and quantities that establish equilibrium in several related markets by maximizing net social benefit. The model takes as its data the technological coefficients on production activities, levels of fixed resources, demand relationships for final products, and supply relationships for purchased inputs and generates a solution that gives the equilibrium prices and quantities of final goods, the pattern of use of the factors of production, prices for purchased inputs, and imputed prices for owned resources and production activities. The equilibrium established by the model is partial because consumer income and the prices of commodities produced outside the sector are held fixed. In specifying this model, we assume that the sector is composed of many competitive agents none of whom can, through their individual actions, influence prices.

The constrained optimization estimates profit-maximizing levels of factor inputs, environmental emissions, crop and livestock production, processed agricultural products, commodity and processed product prices, and final demand sectors, including domestic use, exports, and government and commercial stocks (fig. 1). Geographic coverage for crop production encompasses 90 regions determined by the intersection of the 10 USDA Farm Production Regions, 25 USDA Land Resource Regions, and soil erodibility classification (fig. 2). Geographic coverage for livestock production encompasses 10 regions based on the 10 USDA Farm Production Regions. Twenty-three inputs and their costs (e.g., land, nitrogen fertilizer, energy, and labor) are represented, as well as 44 agricultural commodities (e.g., hogs for slaughter and corn) and processed products (e.g., soybean meal, retail cuts of pork, and ethanol) (table 1).

Crop production activities in each region are differentiated by crop, rotation, and tillage practice. Each production activity contains information on input use, output, and environmental indicators. Production, land use, land use management (crop mix, rotations, and tillage practices), and nitrogen fertilizer application rates are endogenously determined. Allocation of cropland to crop rotations and associated tillage practices is represented with constant elasticity of transformation functions. The transformation function determines the rate at which production practices can be substituted for each other. Regional supplies of crop-specific acreage are represented with positive mathematical programming (PMP) cost functions, while the availability of cropland is represented with simple kinked supply functions. In this framework, cropland is simultaneously allocated to specific crops, specific crop rotations, and specific tillage practices. A constant elasticity of transformation (CET) function, which controls the allocation of land to tillage practices, is defined for each crop rotation. These tillage transformation functions are then nested within the CET transformation functions that control the allocation of land to crop rotations. The parameters of the CET and PMP functions are specified so that model supply response at the national level is consistent with supply response in the USDA's Food and Agriculture Policy Simulator (FAPSIM)(Price, 2004). FAPSIM is an econometrically estimated national-level dynamic simulation model of the U.S. agriculture sector. The nitrogen fertilizer application rate for each production activity is linked to yield by using a nitrogen yield response function.

Livestock production in each region is represented within an activity analysis framework. Production practices are differentiated by livestock type and type of operation. Livestock production activities incorporate yields and input use (including feed nutrient requirements and input costs), and they generate manure and its associated nutrient composition per unit of production activity. Species-specific PMP cost functions are defined for each region. Regional supplies of pasture are represented with simple kinked supply functions derived from pasture supply elasticities.

Major government agricultural programs, including income and price support and the Conservation Reserve Program (CRP), are also represented within REAP. Conservation compliance restrictions on use of highly erodible land (HEL) can also be incorporated into an equilibrium solution. For many environmental policy analyses, conservation compliance is particularly important as it limits expansion of production onto HEL by requiring producers to forgo fixed, counter-cyclical, and CRP payments if they choose to bring new HEL into production.

Processing of primary crop and livestock products is represented at the national level. Processing activities represented for crops include conversion of crops into livestock feed, crushing of soybeans into oil and meal, and conversion of corn into ethanol and associated byproducts (corn gluten feed, corn gluten meal, corn oil, and distiller’s dried grains). Livestock and crop production are connected through the competition for land and conversion of crops into livestock feed. The conversion of crops into livestock feed is represented with a feed mix model that converts crops into their nutritional components, e.g., metabolizable energy and protein, and uses them to produce feed rations for beef and dairy cattle, hogs, and poultry. Rations are differentiated by the proportions of crops, soybean meal, and corn byproducts they contain. Rations defined are based on historical ranges of crop and meal proportions and substitution of corn byproducts for feed grain and soybean meal into those rations. Dairy products are processed into fresh milk, cheese, butter, and evaporated dry milk.

On the demand side, domestic use, trade, ending stocks and price levels for crop and livestock commodities, and processed or retail products are determined endogenously. Trade is represented with export demand and import supply functions. Hence, trade volumes respond to changes in the endogenously determined prices.

Foundations

REAP is a nonlinear, price-endogenous, mathematical programming model of the U.S. agricultural sector. Mathematical programming models have been widely used to model the interaction between agriculture production and the environment at the farm, watershed, and sector level.

Samuelson (1952) was the first to demonstrate that the spatial equilibrium problem could be cast and solved as a constrained maximization problem. Takayama and Judge (1971) demonstrated how linear supply and demand equations could be incorporated and solved as a quadratic programming model. McCarl and Spreen (1980) discussed the properties of price equilibrium models that could be formulated with implicit supply relationships. They demonstrated that a sectoral-level analysis of the type being considered here may be effectively conducted by using a price-endogenous, mathematical programming model.

Several characteristics of programming models are useful in the analysis of the interaction between agricultural production and the environment. First, the structure of these types of models is well suited for imposing resource and policy constraints. The explicit representation of production activities permits the analyst to identify resource use and environmental emissions associated with production and to place constraints on their use. Second, the use of fixed-proportion production technology used in most programming models has had intrinsic appeal (Howitt, 1995). Third, the representation of production activities is consistent with the manner in which production systems are represented within biophysical simulation models. Fourth, it is relatively easy to introduce new or alternative production activities. Fifth, programming models can be constructed from limited historical data, permitting full use of available information. The availability of time series covering the economic and environmental variables of interest is minimal; usually, information is only available to generate one observation per production system. This is not to imply that the data requirements of programming models are trivial. The data requirements for such models are extensive, and the time and manpower needed can be overwhelming (McCarl and Spreen, 1980). Finally, programming models permit detailed analysis of the effects of policy changes across commodities, regions, and production systems.

Despite their appeal, the extension of programming models beyond farm or regional analysis to sector analysis has been limited by their inability to replicate observed patterns of production. This is often the result of the overspecialization problem (Howitt, 1995; McCarl and Spreen, 1980; Preckel et al., 2002). Overspecialization occurs in activity analysis models because the marginal rate of transformation among production activities is constant. This means that the rate at which the inputs can be switched from the production of one good to another does not change. Because the marginal rate of transformation among production activities remains the same regardless of the quantity of inputs already devoted to the production of a particular good, programming models will allocate all inputs to the production activity with the highest net return unless constrained by resource availability.

Before the development of currently available modeling constructs, activity models relied on fixed technologies that necessitated the use of arbitrary upper and lower bounds on the activities to avoid overspecialization. Unfortunately, flexibility constraints, particularly at the sector level, contained little technological or economic information. As a result, the model response was being controlled by constraints that did not reflect limitations imposed by technology or economic behavior. Many solutions to the overspecialization or the calibration problem have been suggested, ranging from greater spatial disaggregation to making commodity prices endogenous, to incorporating risk-averse behavior, to specifying multicommodity demand functions, to using linear combinations of historical distribution of production activities, to specifying cost functions for each production activity. Only the specification of cost functions has proven very satisfactory.

Positive mathematical programming (PMP), formally articulated by Howitt (1995), is the most popular approach used for representing these production activity cost functions. In the PMP methodology, crop-specific cost functions are used to eliminate the need for flexibility constraints. At the sector level, commodity supply elasticities can be used to derive the PMP functions so that supply response reflects the historical data. Cross-supply effects, other than those caused by allocation constraints placed on inputs such as land, labor, and water, can be implicitly included in the parameters of production or cost functions (Paris and Howitt, 1998).

REAP uses an approach developed for calibrating and specifying programming models. It permits the degree of spatial and production disaggregation required for environmental analysis but eliminates the need to use flexibility constraints. The approach extends the PMP formulation by nesting sets of nonlinear transformation functions under the PMP formulation. The use of transformation functions differ from flexibility constraints in that, unlike flexibility constraints, they represent constraints imposed by our assumptions about the production technology.

This approach builds on the foundations laid by both positive mathematical programming and computable general equilibrium (CGE) modeling. The approach is similar to the technique used by Dervis et al. (1982) to specify country-specific export demand functions in CGE models in that it uses a functional form—a constant elasticity of transformation function—that can be specified by using prices, quantities, average costs, and an assumed elasticity of substitution. The approach also borrows from PMP in that it uses shadow prices from calibration constraints to obtain the difference between average and marginal returns needed to specify transformation function parameters.

In REAP, we assume that producers determine the crop they desire to produce, the rotation they will use to produce it, and the tillage practice they will employ. In REAP, PMP functions are used to represent the positively sloping marginal cost curves for the land allocation decision at the crop level. The functions are specified so that the resulting supply functions are consistent with supply response elasticities derived from the FAPSIM model. We then nest two sets of transformation functions under the crop-level PMP functions. The first set of CET functions allocates cropland to various crop rotations. The second set of CET functions allocates rotation acreage to the available tillage practices. This formulation results in a smooth response of acreage planted to changes in relative returns among production enterprises, in accordance with our neoclassical economic behavioral expectation of profit maximization. By using this approach, we avoid the problems of overspecialization and corner solutions that result from using linear activity analysis formulation.

Figure 3 illustrates the overspecialization problem. The transformation curve, CET, represents the maximum amount of a corn soybean rotation (RCB) attainable given the amount of continuous corn rotation (RCCC). The shape of the CET curve determines the rate at which RCB acres can be transformed into RCCC acres. The shape is drawn as it is represented in REAP and indicates that the marginal rate of transformation between RCB and RCCC is declining. When the elasticity of transformation, σ, equals zero, the CET curve takes the familiar corner shape associated with fixed-resource transformation. This indicates that the amount of cropland that can be converted into RCCC and RCB is fixed. When $\sigma = \infty$, the transformation curve becomes a straight line, indicating that the activities are perfectly substitutable. This is the shape of the transformation curve in activity analysis and linear programming models.

The terms of trade, R_1 and R_2, show the rate at which RCB can be exchanged for RCCC given total expenditures and prices. The slope of the terms-of-trade line—or relative price ratio—is given by P_{rccc}/P_{rcb}. As P_{rccc} increases relative to P_{rcb}, the slope of the terms-of-trade line will increase, causing it to become steeper. This implies that as the relative price of RCB to RCCC falls, the amount of land devoted to RCB used will fall and the amount of land devoted to RCCC will increase.

In figure 3, equilibrium occurs at the point where the CET curve is tangent to the terms-of-trade line. This is also the point where the marginal rate of transformation equals the terms-of-trade. When the expenditure line is R_1, equilibrium occurs at Q^1_{RCB} and Q^1_{RCCC}. As RCB becomes relatively less profitable than RCCC at P_{rccc}, the revenue line shifts to R_2, the use of RCB decreases, and RCCC increases until a new equilibrium is established at Q^2_{RCB} and Q^2_{RCCC}.

When $\sigma = 0$, the amount of each production activity used will remain unchanged no matter how the terms of trade change. When $\sigma = \infty$, as it is in linear programming models, only one of the production activities will be used, since the expenditure line becomes tangent to the transformation curve only at a boundary point. This also implies that the amount of a production activity used will only change when the terms of trade change sufficiently to make it more profitable to use the other production activity. When this occurs, the original production activity will no longer be used, since production shifts completely to the new activity. This is what occurs when the terms-of-trade line shifts from R_1 to R_2. In figure 3, when the terms of trade are at R_1, all land is devoted to RCB. If the terms of trade change to R_2, indicating that returns to RCCC are now greater than returns to RCB, all the land is allocated to RCCC.

To prevent this type of overspecialization, some models rely on flexibility constraints to limit movement along the transformation curve. This is depicted in figure 4, where the dark grey shaded block depicts the upper bound placed on RCB use by the flexibility constraint. The heavy straight black line represents the linear transformation curve. However, when the terms of trade change from R_1 to R_2, all land will be shifted to RCCC, and RCB use will go to zero. It is possible to prevent this from happening by using a flexibility constraint to place an upper bound on RCCC use as well. This is shown by the light grey shaded box in figure 4. The problem is how to identify where to place those constraints. Even with an upper bound to restrict movement of land to RCCC, notice that any change will still occur as a corner solution. Because flexibility constraints have no economic or technological justification, you will still have constraints that contain no relevant information determining the solution. By using the CET function approach, we avoid this problem.

Environmental Modeling

Unique features of REAP are its explicit environmental modeling of agricultural activities and calibration to observed environmental data. Environmental effects of crop production activities are obtained from simulations of the production activities using the Environmental Policy Integrated Climate (EPIC) model. EPIC uses information on soils, weather, and management practices, including specific fertilizer rates, and produces information on crop yields, erosion, and chemical losses to the environment. EPIC has been continuously updated since the early 1980s by a team of researchers from the U.S. Department of Agriculture's Agricultural Research Service, Natural Resources Conservation Service (formerly the Soil Conservation Service), and Economic Research Service (ERS), as well as scientists at the Texas Agricultural Experiment Station. EPIC is a field-scale model that uses a daily time step to calculate the fate of various environmental parameters under different tillage, crop rotation, soil management, and weather scenarios. Although originally developed specifically to analyze the extent and costs of soil erosion, the model has been expanded over the years to simulate and provide information on hydrology, erosion, nutrient cycling, pesticide fate, soil temperature, and crop growth and yield. In addition to the effect of production practices on yields, EPIC is used to estimate the effect of production practices on yield, as well as to compute environmental indicators such as nitrogen loss and greenhouse gas emissions per acre for each REAP crop system.

Management practices and initial fertilizer application rates are consistent with agronomic practices for the 45 regions as reported in USDA's Cropping Practices Survey. Yield and environmental indicators are estimated by running each of the cropping systems represented in REAP through EPIC. The set of environmental indicators represented includes soil erosion (water and wind), losses of nitrogen and phosphorus to ground and surface water, nitrogen runoff damage to coastal waters, and erosion damage and losses of nitrogen to the atmosphere through volatilization and denitrification, carbon sequestered by soils, greenhouse gas emissions associated with machinery use and fertilizer production, and pesticides lost to ground and surface waters. Livestock waste and associated nutrient emissions are derived from formulas used in Kellogg et al. (2000). These formulas are adjusted to account for differences in timeframes represented by REAP production activities and production activities in the report.

Onsite phosphorus and nitrogen runoff estimated by EPIC are calibrated to in-stream measurements made by the U.S. Geological Survey (Smith et al., 1997). The transport coefficients for phosphorus and nitrogen are used to estimate the quantity of sheet and rill erosion and pesticides that also run off into surrounding water bodies. Pesticide leaching and runoff are measured by the active ingredient quantity and then normalized to reflect toxicity and half-life (Barnard et al., 1997).

Estimates of offsite damages are derived from sediment and nitrogen damage indexes developed by USDA (Claassen et al., 2001). Amenities included in the indexes are municipal water use, industrial uses, irrigation ditch maintenance, road ditch maintenance, water storage, flooding, and soil productivity, as well as fresh-water-based recreation, navigation, estuary-based boating, swimming, and recreation. These do not reflect all amenities affected by sediment and nitrogen runoff, so the offsite damage estimates should be viewed as a lower bound. Table 2 lists the environmental parameters REAP estimates in each model run.