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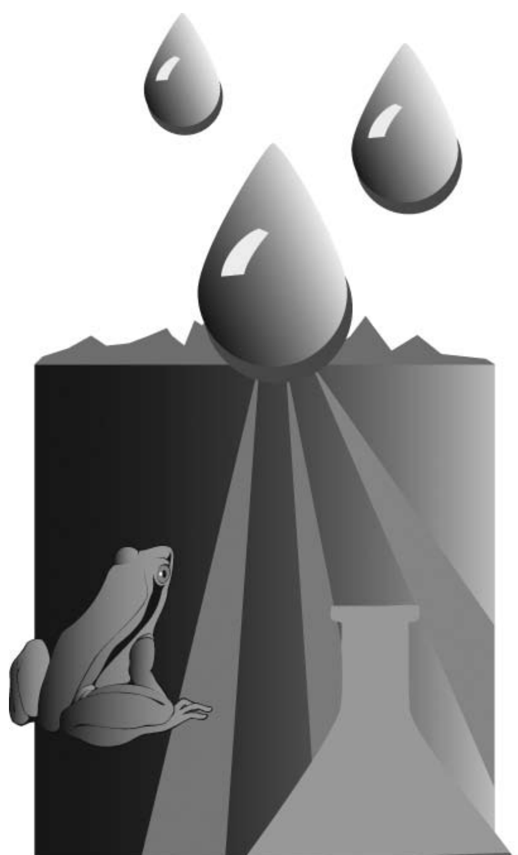
Model Simulation of Soil Loss, Nutrient Loss, and Change in Soil Organic Carbon Associated with Crop Production



Steven R. Potter
Texas Agricultural Experiment Station
Blackland Research Center
Temple, TX

Susan Andrews
U.S. Department of Agriculture
Natural Resources Conservation Service
Greensboro, NC

Jay D. Atwood
U.S. Department of Agriculture
Natural Resources Conservation Service
Blackland Research Center
Temple, TX

Robert L. Kellogg
U.S. Department of Agriculture
Natural Resources Conservation Service
Beltsville, MD

Jerry Lemunyon
U.S. Department of Agriculture
Natural Resources Conservation Service
Blackland Research Center
Temple, TX

Lee Norfleet
U.S. Department of Agriculture
Natural Resources Conservation Service
Blackland Research Center
Temple, TX

Dean Oman
U.S. Department of Agriculture
Natural Resources Conservation Service
Beltsville, MD

Note: After the senior author, co-authors are listed in alphabetical order.

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Purpose of study

The purpose of this study is to identify cropland areas of the country that would benefit the most from the application of conservation practices. The 1997 National Resources Inventory (NRI) was used with other national-level databases to develop a simulation model. The simulation model provided estimates of eight onsite (field-level) environmental outcomes representing about 80 percent of the cropland acres in the United States (see box inset Modeling Onsite Environmental Outcomes):

- sediment loss from water erosion (ton/a/yr sediment yield, not including ephemeral or other gully erosion)
- wind erosion rate (ton/a/yr)
- nitrogen lost with waterborne sediment (lb/a/yr)
- nitrogen dissolved in surface water runoff (lb/a/yr)
- nitrogen dissolved in leachate (lb/a/yr)
- phosphorus lost with waterborne sediment (lb/a/yr)
- phosphorus dissolved in surface water runoff (lb/a/yr)
- soil quality degradation indicator

Terraces, stripcropping, contour farming, and residue management practices were included in the analysis; other conservation practices such as buffers, grassed waterways, and nutrient management practices were not included. Thus, results are presented as *potential* losses of soil and nutrients from farm fields and the *potential* for soil quality degradation. Limitations such as incomplete cropland coverage in some regions, the lack of site-specific management practices including crop rotations, and modeling limitations noted in the report are additional reasons to consider the model output as potential losses of soil and nutrients.

Efforts are currently underway within the Conservation Effects Assessment Project (CEAP) to improve the modeling routines, obtain more complete site-specific information, and more fully account for conservation practice effects. CEAP is a multi-agency effort initiated in 2003 to estimate the environmental benefits of conservation practices at national and regional levels and to conduct case studies on the effects of conservation practices in selected watersheds.

Assessment of priority acres

Priority acres—those most in need of conservation treatment—are critical acres for one or more of the eight onsite environmental outcomes. For each outcome, critical acres were identified as acres with the highest loss estimates (or lowest soil condition rating in the case of soil quality) in the country. In many cases, cropland acres were critical for multiple outcomes. Five categories of priority acres, each representing different thresholds of severity, are presented and discussed in the report. These range from the

Modeling onsite environmental outcomes

A microsimulation modeling approach was used to estimate loss of potential pollutants from farm fields and changes in soil organic carbon. The 1997 NRI provided the analytical framework. Data on farm-level management was derived from farmer surveys and other national level databases, and data on land use and soil characteristics were provided by the NRI. The physical process model EPIC (Environmental Policy Integrated Climate) was used to estimate surface water runoff, percolation, wind erosion, sediment loss, nutrient loss, and changes in soil organic carbon for each NRI cropland sample point included in the study. Over 750,000 EPIC model runs were conducted to obtain the results summarized in this report. Model results were estimated for 15 crops representing approximately 298 million acres, or 79 percent, of United States cropland, exclusive of acres enrolled in the Conservation Reserve Program. Horticultural crops such as fruit and nuts and most vegetables were not modeled, nor were all cropland areas in the West. As a result, some areas of the country—especially the West, Florida, and parts of New England—are not well represented in these simulations.

EPIC is a point model that has been developed and parameterized on the basis of measured research data from experimental research plots and small fields. The model outputs, such as surface water runoff or sediment yield, are similar to what would be found if actual measures could be taken from the edge of an area within a field about 1 hectare (2.5 a) in size that was reasonably homogeneous. Vertically, EPIC simulates fate and transport processes through the soil profile. Thus, EPIC model output reported in this study is best represented as water, soil, and nutrient loss at the edge of a field or at the bottom of the root zone.

Models such as EPIC use mathematical representations of the real world to estimate the effects of complex and varying environmental events and conditions. They are necessary to simulate systems that are too large or too complex to realistically establish monitoring systems to measure outcomes. Models generally work best in estimating relative changes, are less effective in estimating absolute values, and can never be as accurate as scientific measurements. As applied in this study, model simulation results are used to make spatial comparisons, and so are appropriate for estimating the cropland areas of the country that have the highest potential for soil and nutrient loss. The field-level sediment and nutrient losses estimated in this study are indicators of potential environmental impacts, but they do not necessarily equate to environmental impairment because estimates are not linked to hydrologic models that simulate transport of pollutants offsite (such as to surface water bodies or ground water aquifers).

The simulation model incorporates a large amount of both physical and management data and accounts for most of the major processes involved with fate and transport of soil and nutrients. In some cases, assumptions were used to fill information gaps. In a few cases, however, it was not possible to address important factors for this study. Principal among these were the inability to simulate crop rotations because of the lack of information on farming practices specific to each crop rotation, inability to represent tile drainage or surface drainage systems because of the lack of consistent information on these features at NRI sample points, and the inability to appropriately represent poorly drained field conditions—and associated denitrification processes—during the nongrowing season.

most critical 5-percent category (the 5% of acres with the highest losses or worst soil condition) to the most critical 25-percent category.

Map 1 presents results for the most critical 15-percent category, consisting of critical acres with sediment loss and nutrient loss estimates in the top 15 percent nationally, wind erosion rates in the top 6 percent nationally, and soil quality degradation indicator scores in the bottom 15 percent nationally. Priority acres at this level of severity are concentrated in six areas:

- cropland in the Lower Mississippi River Basin below St. Louis and the lower reaches of the Ohio River—often critical for five or more outcomes
- cropland in the Chesapeake Bay watershed in Maryland and Pennsylvania—significant proportion of the acres were critical for five or more outcomes
- cropland in the southern two-thirds of Iowa and parts of Illinois and Missouri adjacent to Iowa—significant proportion of the acres were critical for 3 to 4 outcomes
- cropland along the Atlantic Coastal Plain stretching from Alabama to eastern Virginia and Delaware—most of the cropland acres in this area were critical for two or more outcomes
- cropland in northwestern Texas
- selected cropland regions in the West

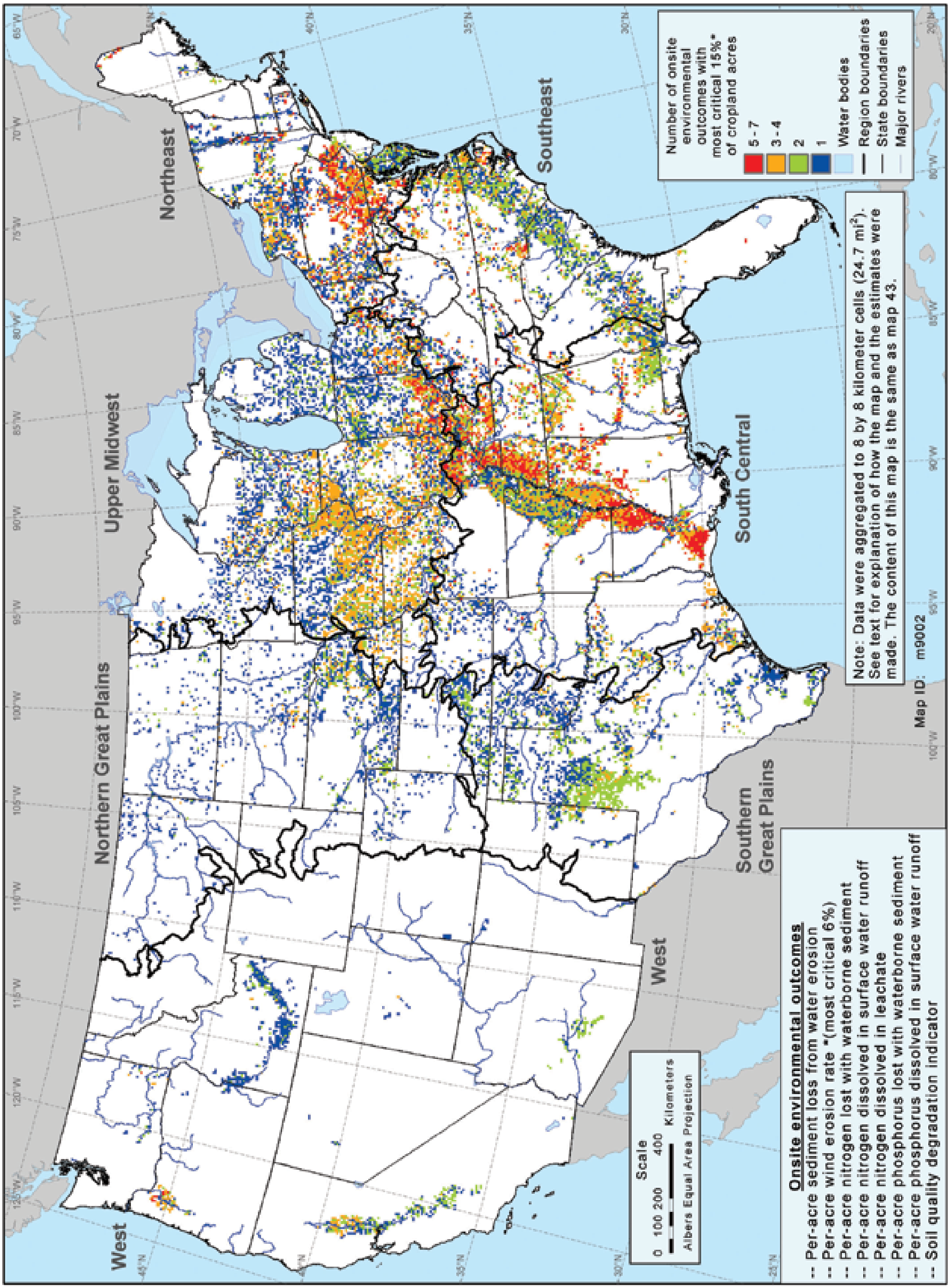
For the most critical 15-percent category, about half (155 million a) of the cropland acres included in the study were critical acres for at least one outcome, about 29 percent (87 million a) were critical for two or more outcomes, about 12 percent (36 million a) were critical for three to four outcomes, and about 4 percent (12 million a) were critical for five or more outcomes.

An assessment of priority cropland acres for all five categories of severity (5-, 10-, 15-, 20-, and 25% categories) leads to the following conclusions:

- Critical cropland acres that are most in need of conservation treatment to manage soil loss, nutrient loss, or soil quality degradation are distributed throughout all the major cropland areas of the country.
- Critical acres are more concentrated in some regions of the country than in other regions.
- Critical acres for multiple onsite environmental outcomes are concentrated in a few cropland areas. These acres should represent the highest priority acres for conservation treatment.
- The loss pathways and specific treatment needs vary from region to region; for example, the most critical acres for nitrogen runoff loss and nitrogen leaching loss are primarily in different cropland areas.

Priority acres are identified in this study on a per-acre basis; that is, those cropland acres where investment in conservation practices would poten-

Map 1 Priority cropland acres with highest potential for soil loss, nutrient loss, and soil quality degradation



tially have the greatest benefits at the field level. Most conservation practices are designed to abate pollution sources at the field level. However, there are other considerations that can factor into the determination of priority areas for conservation program implementation, such as potential for soil and nutrient losses from farm fields to migrate into lakes, rivers, streams, or ground water in sufficient amounts to contribute to water quality impairment; total loadings delivered to sensitive downstream ecosystems including estuaries and coastal waters; and cost effectiveness of conservation practices.

Major findings for onsite environmental outcomes

Cropland that is most in need of conservation practices is determined by the amount and timing of precipitation, field management activities including irrigation, soil characteristics, and the presence or absence of conservation practices. The model simulation results showed that the loss of sediment, nitrogen, and phosphorus can vary considerably from field to field even within fairly small geographic areas. This variability was often related to differences in sources, amounts, and timing of nitrogen and phosphorus inputs, as well as differences in tillage practices. Results presented in the report show that soil texture and hydrologic soil group also accounted for a large part of the variability.

The critical acres identified in the study account for the bulk of the total tons of eroded soil and the total pounds of nutrient loss from all cropland acres. This disproportionality occurs because of a minority of acres with high estimates of losses. For example, the 5 percent of acres with the highest per-acre sediment loss accounted for 34 percent of the total tons of sediment loss estimated for all cropland acres, and the 10 percent of acres with the highest per-acre sediment loss accounted for 50 percent of the total tons of sediment loss. The 2 percent of acres with the highest wind erosion rates accounted for 42 percent of the total tons of wind erosion. This disproportionality was also evident for nitrogen and phosphorus loss.

	Percent of total pounds lost from all cropland acres for the 5% of acres with the highest losses	**Percent of total pounds lost from all cropland acres for the 10% of acres with the highest losses**
Nitrogen dissolved in leachate	44	74
Nitrogen dissolved in surface water runoff	32	57
Nitrogen lost with waterborne sediment	23	47
Phosphorus dissolved in surface water runoff	24	36
Phosphorus lost with water-borne sediment	31	46

Maps presented in the main body of the report identify areas of the country with the greatest potential for loss of soil and nutrients from farm fields and areas with potential for soil quality degradation. For reporting of summary statistics, seven geographic regions were delineated on the basis of similar hydrologic characteristics (precipitation, surface runoff, and percolation), shown on map 1.

Northeast region. Critical acres in the Northeast region were largely the result of sediment loss from water erosion and nitrogen and phosphorus lost with waterborne sediment. For these three outcomes, the Northeast region had the highest average losses of any of the seven regions. Sediment loss averaged 3.2 tons per cropland acre per year in this region, and nitrogen and phosphorus lost with waterborne sediment averaged 13 and 3 pounds per acre per year, respectively. Nitrogen and phosphorus dissolved in surface water runoff were also important determinants of critical acres in the Northeast region. High levels of nitrogen dissolved in leachate contributed to critical acres in some places. Many of the critical acres in the Northeast region had high losses for multiple outcomes.

Upper Midwest region. Critical acres in the Upper Midwest region were also primarily the result of sediment loss and nitrogen and phosphorus lost with waterborne sediment. Estimates of nitrogen and phosphorus lost with waterborne sediment in the Upper Midwest region were second only to those in the Northeast, averaging 12 and 2 pounds per acre, respectively. Sediment losses averaged 2 tons per acre, which ranked third among the seven regions. High levels of nitrogen dissolved in surface water runoff and in leachate and phosphorus dissolved in surface water runoff were also determinants of critical acres in some places.

South Central region. The most densely concentrated critical acres for multiple onsite environmental outcomes in the country occurred along the Mississippi River within the South Central region. All outcomes except wind erosion contributed significantly to critical acres in this region. Average per-acre estimates of sediment loss, nitrogen dissolved in surface water runoff, nitrogen dissolved in leachate, and phosphorus dissolved in surface water runoff were the second highest among the seven regions. Per-acre estimates of nitrogen and phosphorus lost with waterborne sediment were the third highest among the regions. The potential for soil quality degradation was also high in this region.

Southeast region. The predominant determinant of critical acres in the Southeast region was nitrogen dissolved in leachate. Nitrogen dissolved in leachate averaged nearly 30 pounds per acre per year in the region, which was substantially higher than in any other region. The highest average loss of phosphorus dissolved in surface water runoff was also observed for cropland acres in the Southeast region. In a few places, high levels of sediment loss and nitrogen and phosphorus lost with waterborne sediment contributed to critical acres. The potential for soil quality degradation was high in the Southeast region, as well.

Southern Great Plains region. Wind erosion was the predominant determinant of critical acres in the Southern Great Plains region. Wind erosion averaged over 5 tons per acre per year for cropland acres in this region. Soil quality degradation was also an important determinate of critical acres. In some places, nitrogen dissolved in leachate or surface water runoff contributed to critical acres.

Northern Great Plains region. Critical acres in the Northern Great Plains region were less dense than in other regions, although critical acres were distributed throughout all cropland areas in the region. The predominant cause for critical acres in this region was wind erosion. The potential for soil quality degradation also accounted for a significant number of critical acres.

West region. Only the major cropland areas in the West were included in the study, representing about 25 percent of the cropland in the region. About 80 percent of the acres included in the study in the West region were irrigated. For these areas, the predominant determinant of critical acres was high levels of nitrogen dissolved in surface water runoff from irrigated acres, with highest losses in the Snake River Basin in Idaho, central California, and southern Arizona. Phosphorus dissolved in surface water runoff was an important determinant of critical acres in some places. The potential for soil quality degradation was also a significant factor in California and Arizona. The Willamette River Basin had a concentration of critical acres for multiple environmental outcome categories, including sediment loss, nitrogen and phosphorus lost with waterborne sediment, and nitrogen dissolved in leachate.

Effects of tillage. Model simulation results obtained in this study accounted for the effects of residue management by simulating three tillage types—conventional tillage, mulch tillage, and no-till. Tillage practices have a direct influence on sheet and rill and wind erosion processes. A subset of model runs where all three tillage systems were included in model simulations was used to assess the effects that tillage had on wind erosion, sediment loss, and nutrient loss estimates. This tillage comparison subset of model runs included eight crops and represented about 70 percent of the cropland acres covered by the study. Acreage representation of the three tillage systems in this tillage-effects baseline was: 59 percent for conventional tillage, 21 percent for mulch tillage, and 21 percent for no-till. When compared to model simulation results assuming 100 percent of the acres had conventional tillage, these tillage practices accounted for:

- 32 percent reduction in sediment loss (0.8 ton/a/yr reduction, on average)
- 26 percent reduction in wind erosion rates (0.3 ton/a/yr reduction, on average)
- 7 percent reduction in nitrogen loss (3.2 lb/a/yr reduction, on average)
- 13 percent reduction in phosphorus loss (0.4 lb/a/yr reduction, on average)

Effects of terraces, contour farming, and stripcropping. Three conservation practices—contour farming, stripcropping, and terraces—were shown to have a significant influence on sediment loss and nutrient loss estimates in the model simulations. These three practices are used on about 32 million acres, or about 10 percent of cultivated cropland, according to the 1997 NRI. For comparison to the results for the model runs that included these three conservation practices, an additional set of model runs were conducted after adjusting model settings to represent no practices. For acres that had one or more of these three conservation practices:

- sediment loss was reduced 54 percent (1.8 ton/a/yr reduction, on average)
- nitrogen loss was reduced 16 percent (7 lb/a/yr reduction, on average)
- phosphorus loss was reduced 28 percent (1 lb/a/yr reduction, on average)

Reductions in sediment and nutrient loss varied considerably by region, with the highest reductions generally found in areas with the highest loss estimates.

Model Simulation of Soil Loss, Nutrient Loss, and Change in Soil Organic Carbon Associated with Crop Production

Introduction

About half of the land area in the United States, exclusive of Alaska, is cropland, pastureland, and rangeland owned and managed by farmers and ranchers. About 20 percent—377 million acres—is intensively managed to produce crops (USDA NRCS 2000). American farmers produce over 200 different crops, although five crops (cotton, hay, wheat, corn, and soybeans) account for about 70 percent of the total cropland acreage each year (USDA NASS 2004).

Soil properties and landscape characteristics vary considerably on land used to grow crops in the United States, as do climatic conditions. As a result, the crop mix and specific crop production practices (tillage, nutrient applications, pesticide applications, irrigation practices) differ substantially from one part of the country to another. If appropriate management activities and conservation practices are not used, the interaction between wind and water, soil and landscape characteristics, and crop production practices results in the loss of soil, nutrients, and pesticides from farm fields, contributing to water quality degradation in some watersheds. Moreover, onsite soil erosion and soil quality degradation, if not addressed, can jeopardize prospects for sustaining future crop production.

Science has shown that not all cropland acres are equally vulnerable to the forces of wind and water that cause the migration of potential pollutants from farm fields to lakes, rivers, streams, and ground water. The National Resources Inventory (NRI) documents how a minority of cropland acres (those most prone to erosion) are the source of the majority of the overall soil erosion (H.J. Heinz Center 2002). Various watershed modeling projects have shown that water quality degradation can be ameliorated by addressing resource concerns in only a portion of the watershed. Studies on the human dimension have also shown that the potential for environmental degradation can often be disproportionately influenced by a small group of land users (Shephard 2000). Nowak and Cabot (2004) argue that incorporation of this concept of disproportionality into water resource management is necessary to attain cleaner, healthy watersheds in agricultural areas. Understanding the characteristics and spatial distribution of the more fragile, or vulnerable, cropland acres can lead to more efficient and effective implementation of conservation programs.

The purpose of this study is to identify areas of the country that have the highest potential for sediment and nutrient loss from farm fields, wind erosion, and soil quality degradation—areas of the country that would likely benefit the most from conservation practices. To accomplish this, the National Nutrient Loss and Soil Carbon (NNLSC) database was constructed using the 1997 NRI to represent cropland land use patterns and resource conditions. The modeling results reported in this study were obtained using a system of databases and models built by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) and the Blackland Research Center, Texas Agricultural Experiment Station (TAES) during 2000 to 2004. The spatial distribution of the model outputs is shown in maps to identify areas of the country with the greatest potential for loss of soil and nutrients from farm fields and for changes in soil organic carbon as an indicator of the potential for deteriorating soil quality.

This report is the first in a series of reports on the cropland national assessment component of the Conservation Effects Assessment Project (CEAP). CEAP is a multi-agency effort initiated in 2003 by five USDA agencies (NRCS, ARS, CSREES, FSA, and NASS) to estimate the environmental benefits of conservation practices (Mausbach and Dedrick 2004). The purpose of the project is to quantify the benefits and effects of conservation practices. The project has two principal components: the watershed assessment studies component, designed primarily to measure the effects of conservation practices at the watershed scale, and the national assessment, designed to provide estimates of the benefits of conservation practices for reporting at the national and regional levels. (More information about CEAP can be found at *http://www.nrcs.usda.gov/technical/nri/ceap*.)

Subsequent CEAP reports on cropland will expand and extend the results presented in this first report.

A new farmer survey—the NRI–CEAP cropland survey—was initiated in 2003 to provide better and more current information on farming activities and conservation practices at NRI sample points (USDA NRCS 2004). In addition, significant refinements are currently underway in the models and modeling systems used to estimate effects. Preliminary results based on the new and expanded models and databases are scheduled for release in 2006, followed by a final report in 2007. Results in these forthcoming CEAP reports are expected to differ somewhat from results reported in the present study, benefiting from improved model routines, better information on farming activities, and a fuller accounting of conservation practices.

Modeling approach and methods

Overview of approach

The modeling approach used in this study is based on microsimulation modeling techniques that were originally developed to investigate the economic impact of public policy (Haveman and Hollenbeck 1980a, 1980b; Lewis and Michel 1989). Microeconomic simulation models consist of microdata on characteristics of individuals obtained from statistically designed surveys and response functions that predict behavior of individuals. Macroeconomic outcomes are then obtained by aggregating predicted outcomes of individuals represented in the sample. The statistical sample design provides the basis for the aggregation.

A similar modeling approach is used in this study. The 1997 NRI provides the microdata on natural resource characteristics for a representative set of sample points. The NRI is designed to assess conditions and trends of soil, water, and related resources on private land (see box inset—The National Resources Inventory). It consists of about 800,000 sample points, of which about 220,000 were cropland in 1997. NRI information on crop, soil characteristics, and other information for the year 1997 are combined with data on field management activities from farmer surveys and other sources for a comparable time period and used in conjunction with a field-level fate and transport process model to estimate the loss of materials from farm fields and other outcomes such as the change in soil organic carbon. The statistical sample weight associated with each sample point is used to aggregate the model outputs to the national or regional level. The resulting simulation model captures the diversity of land use, soils, climate, and topography from the NRI, estimates the loss of potential pollutants from farm fields at the field scale where the science is best developed, and provides a statistical basis for aggregating results to the national and regional levels. NRCS and TAES have used this approach in previous studies to estimate pesticide loss from cropland (Kellogg et al. 1992, 1994; Kellogg et al. 2002; Goss et al. 1998; Goebel and Kellogg 2002) and to identify priority watersheds for water quality protection from non-point sources related to agriculture (Kellogg 2000; Kellogg et al. 1997).

The physical process model Environmental Policy Integrated Climate (EPIC) is used to generate estimates of soil loss, loss of nutrients, and change in soil organic carbon for the 1997 NRI cropland sample points. (A description of the EPIC model is presented in a later section.) Version 3060 of EPIC was used. The Interactive-EPIC (I–EPIC) software (Campbell 2005; Gassman et al. 2003) was used to manage and automate batch model runs. An application program called RunBuilder was developed to automate data assembly. The integrated modeling system consists of the EPIC model, I–EPIC model management software, input databases, RunBuilder, and the model output database. The modeling system is documented in Potter et al. (2006).

The goal is to produce estimates of soil loss, nutrient loss, and change in soil organic carbon at NRI cropland points. However, it is not practical or necessary to run EPIC at each NRI sample point. Many of the sample points have the same crop grown on similar soils and in similar climates. Instead, a library of EPIC model results called the National Nutrient Loss and Soil Carbon (NNLSC) database was produced that provides estimates of EPIC model output for specific crops, soils, climates, and management characteristics. These EPIC model results were then matched to NRI sample points on the basis of the attributes associated with each sample point.

The National Resources Inventory

The National Resources Inventory (NRI) is a scientifically-based survey designed to assess conditions and trends of soil, water, and related resources of the Nation's non-federal lands at the national and regional level (USDA NRCS 2000; Goebel 1998).

The NRI sample is a stratified two-stage unequal-probability area sample (Nusser and Goebel 1997; Goebel and Baker 1987). The primary sampling units (PSU) are areas of land called segments. The segments vary in size from 16 to 256 hectares (40–640 a). Sampling rates vary across strata, but are typically between 2 and 6 percent. There are about 300,000 sample segments in the current national sample. Detailed data are collected at a randomized sample of points within each of these segments. Generally, there are three points per segment, but some segments only contain one or two points. Overall, there are about 800,000 sample points in the NRI, representing all land uses on privately owned land in the United States. The NRI sample was designed to provide national, state, and in some cases, sub-state assessments with statistical reliability.

At each sample point, information is collected on nearly 200 attributes including land use and cover, soil type, cropping history, conservation practices, erosion potential, water and wind erosion estimates, wetlands, wildlife habitat, vegetative cover conditions, and irrigation method. Detailed NRI data are collected for the specific sample points, but some items are also collected for the entire primary sampling unit. Some data, such as total surface area, federally owned land, and areas in large water bodies, are collected on a census basis external to the sample survey. Data are collected for PSUs using photo-interpretation and other remote sensing methods and standards. Data gatherers also use ancillary materials such as USDA field office records, information from NRCS field staff, soil survey and other inventory maps and reports, and tables and technical guides developed by local field office staffs. Data gathered in the NRI are linked to NRCS Soil Survey databases and can be linked spatially to climate databases.

The NRI approach to conducting inventories facilitates examining trends over time because the same sample sites have been studied since 1982, the same data have been collected since 1982 (definitions and protocols have remained the same), and quality assurance and statistical procedures are designed/developed to ensure that trend data are scientifically legitimate and unambiguous. Data undergo rigorous quality review. Statistical estimation procedures are used to assign acreage weights—called expansion factors—to sample points based on sampling (selection) probabilities, estimates from previous NRIs, and known land base attributes from the Census Bureau and other sources.

The 1997 NRI is the most recent published database. It includes sample point data for 4 years—1982, 1987, 1992, and 1997. The NRI is currently in transition from a 5-year cycle to an annual cycle of data collection. Summary statistics for the 2003 NRI have been released, but the sample point database is not yet available.

For more information on the NRI, visit *http://www.nrcs.usda.gov/technical/NRI/*.

The NNLSC database consists of EPIC model results for 25,250 Unique Resource Units (URU). Each URU consists of a climate zone, a soil cluster, a specific state, a specific crop, one of three irrigation types including no irrigation, and one of eight combinations of three conservation practices (contour farming, stripcropping, and terraces) including no practices (fig. 1). For modeling purposes, each URU is treated as a single homogeneous farm field. Several EPIC model runs are made for each URU, representing different tillage systems, different commercial fertilizer application schemes, and two types of manure applications. More model runs were conducted for URUs with a diverse collection of tillage and nutrient application possibilities than URUs with less diversity. Some crops, for example, have more tillage and nutrient application possibilities than other crops, and these can also vary for a given crop by region of the country. An average of 30 EPIC model runs were made for each URU to represent the various tillage options, commercial fertilizer application options, and manure application options. (The data inputs and assumptions used to generate these simulations are presented in later sections.) A total of 768,785 EPIC model runs were made to generate the NNLSC database.

The characteristics that define a URU (climate zone, soil cluster, state, crop, irrigation system, and conservation practice) were derived from characteristics of NRI cropland sample points. For example, the presence of irrigation, contour farming, stripcropping, and terraces was obtained from the NRI. Each URU represents at least one NRI cropland sample point. On average, a URU represents seven NRI sample points, with a maximum of 830 sample points in the largest URU. The acreage representation of each URU is the sum of the expansion factors for the NRI points corresponding to the URU. URUs with less than 1,000 acres were discarded because model simulation of these small areas would contribute little to the overall assessment; the corresponding NRI sample points were excluded from the sample domain.

Figure 1 Organizational scheme for construction of the NNLSC database

Climate zone (66 climate zones)
Soil clusters (2,688 soils with 5,887 soil-climate combinations)
State (48 states with 6,043 state-soil-climate combinations)
Crop (15 crops)
Irrigation system (sprinkler, furrow, no irrigation)
Three conservation practices (8 combinations)
|
25,250 URUs
Tillage system (3 types)
Commercial fertilizer application
Manure application
|
768,785 EPIC model runs

Each EPIC model run consists of 40 consecutive years of which the last 30 years of annual output were saved for analysis. The first 10 years of results are dropped because the model uses default starting values for various soil attributes and other input data (such as crop residue levels) that are not known, and therefore, the model is allowed to equilibrate before the annual output is recorded. A weather generator was used to provide estimates of daily weather. (Weather simulation is described in a later section.)

All crops were simulated as if they were grown in each year of the 40-year simulation (continuous cropping). Crop rotations can be modeled using EPIC, but the lack of information on the occurrence of the various crop rotations and the paucity of data on nutrient applications and tillage practices for crops grown in specific crop rotations precluded simulation of crop rotations in this study. However, sensitivity analysis showed that varying the crop from year to year sometimes has a significant effect on both the hydrologic cycle and the nutrient cycles, indicating that crop rotations will need to be taken into account in future modeling efforts.

EPIC model outputs were reported as 30-year annual averages. The results can be interpreted as outcomes averaged over a set of weather conditions that could reasonably occur. Alternatively, results represent expected outcomes for a future year where the weather conditions are not known. The cropping patterns and management activities are generally representative of 1997; however, the output results represent outcomes that would be expected after removing the year-to-year variability owing to weather. To estimate the 30-year change in organic carbon, the first and the 30th year values were used.

EPIC model outputs for each NRI cropland sample point were derived from the NNLSC database after obtaining 30-year annual averages for each model run. Model output results for NRI sample points were obtained by calculating the weighted average over all the management options in the NNLSC database for the URU corresponding to the NRI sample point. Each NRI sample point corresponding to a given URU was assigned the same model output results. The weights represent the probability that a particular option would occur. For example, if there were only three management options and the probability that the first option would occur was 20 percent, the probability that the second option would occur was 30 percent, and the probability that the third option would occur was 50 percent, then the model output estimate for the NRI sample point would be 0.2 times the model output estimated by EPIC for the first option plus 0.3 times the model output estimated for the second option plus 0.5 times the model output estimated for the third option. The probabilities that a particular management option applies to a URU (and the associated NRI sample points) were estimated based on the frequency of occurrence of each option obtained from national level databases (see app. A).

National and regional estimates of soil loss, loss of nutrients, and change in soil organic carbon were derived from the EPIC model outputs estimated for each NRI cropland sample point. Aggregated estimates were produced using the statistical sample weight (expansion factor, or acreage weight) associated with each NRI sample point. In the case of per-acre estimates, the expansion factors were used to derive weighted averages. In the case of total loss estimates, the expansion factors served as acreage estimates. In addition, maps showing the spatial distribution of EPIC model outputs were derived from estimates for NRI cropland sample points.

Seven geographic regions were established for reporting and summarizing the model results. The seven regions were determined on the basis of similar hydrologic characteristics (precipitation, runoff, and percolation). More traditional regional boundaries were tried initially, such as combinations of states or large watersheds, but the aggregate results for reporting in tables were in conflict with the information in the spatial distribution maps. These seven regions were selected so that the spatial trends in the maps were reflected in the regional tables. The boundaries for the seven regions are shown on all maps. The seven regions are the Northeast, Southeast, Upper Midwest, South Central, Northern Great Plains, Southern Great Plains, and West. Percent acres represented in the model simulations for each region are:

Region	Percent of total acres
Northeast region	4.6
Southeast region	4.5
South Central region	15.2
Upper Midwest region	37.7
Southern Great Plains region	10.8
Northern Great Plains region	24.3
West region	3.0

In the sections that follow, more details are provided on the EPIC model, the nature and extent of the NRI sample points included in the study, how soil and other characteristics were represented in the model, how weather was simulated, how farming practices and conservation practices were represented, how nutrient management activities were represented, and how the maps of the spatial distribution of the model output were derived.

EPIC model

For crop production, farmers prepare the soil (usually by loosening and mixing it), add fertilizer and organic amendments such as manure or lime, plant the seeds, cultivate, apply chemicals for pest control, irrigate as needed, and then harvest the crop. Throughout the year, weather events affect crop production both positively and negatively. Properties of the soil such as bulk density, organic matter, and water holding capacity affect crop growth and other processes. Over time, the chemical properties and physical structure of the soil can change. As a result of the interaction between the farmer's production activities, soil properties, and weather events, some soil particles are carried off the field by water runoff and wind. Adhered to these soil particles are residues of nitrogen, phosphorus, and pesticides. Nutrients and pesticides also migrate from the field dissolved in the water runoff and in the water that leaches beyond the root zone.

All of these processes are simulated in the EPIC model. A wide variety of soil, weather, and cropping prac-

tice data input options allow simulation of most crops on virtually any soil and climate combination. EPIC is used by scientists throughout the world for studying agro-environmental issues (Putman et al. 1988; Robertson et al. 1990; Sharpley et al. 1991; Stockle et al. 1992; Chang et al. 1993; Lacewell et al. 1993; Mapp et al. 1994; and Wu et al. 1996). EPIC was originally developed in the early 1980s for assessing the impact of agricultural management practices and the associated soil erosion on long-term productivity of United States soils (Putman et al. 1987, 1988; USDA SCS 1989; Williams 1990, 1995). Since then, the EPIC model has been extended to include the major soil and water processes related to crop growth and a broad array of environmental effects of farming activities. It continues to be modified and refined. The most recent version, version 3060, incorporates routines for soil carbon accounting that are nearly identical to those in the Century model, as well as other refinements (Izaurralde et al. 2005; Williams and Izaurralde 2005). Appendix B contains a summary of published literature on EPIC application and performance.

The major model components in EPIC are weather simulation, hydrology, erosion/sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control (fig. 2). EPIC operates on a daily time step, integrating daily weather data, soil characteristics, and farming operations such as planting, tillage, and nutrient applications. The plant growth model simulates the growth and harvest of a crop. All farming operations that take place on the field throughout the year are taken into account. On a daily basis, EPIC tracks the movement of water, soil erosion, and the cycling of nitrogen, phosphorus, and carbon.

EPIC is a point model that has been developed and parameterized on the basis of measured research data from experimental research plots and small fields. EPIC does not recognize field characteristics such as slope, shape, or concentrated flow paths. It does not route soil and water from one part of the field to another part of the field. EPIC assumes that the field area around the point is entirely homogeneous, including soil characteristics and all management activities. One of the ramifications of this is that EPIC does not estimate gully erosion. As a point model, it is ideal for use with NRI sample points because NRI sample points are also points in a field. Because of the nature of the measured data used to develop and parameterize EPIC, the model output represents about a 1-hectare area, or about 2.5 acres. The model outputs, such as surface water runoff or sediment yield, are similar to what would be found if actual measures could be taken from the edge of an area within a field about 1 hectare in size that was reasonably homogeneous. Vertically, EPIC simulates fate and transport processes through the soil profile, which is generally the boundary for crop roots. Thus, EPIC model output reported in this study is best represented as water, soil, and nutrient loss at the edge of a field or a small part of a field and at the bottom of the root zone (Williams 1990).

The potential list of output variables that can be generated by EPIC is large. Only a selection were tracked and reported in this study (table 1).

Figure 2 Schematic representing inputs to, processes in, and outputs from the EPIC model

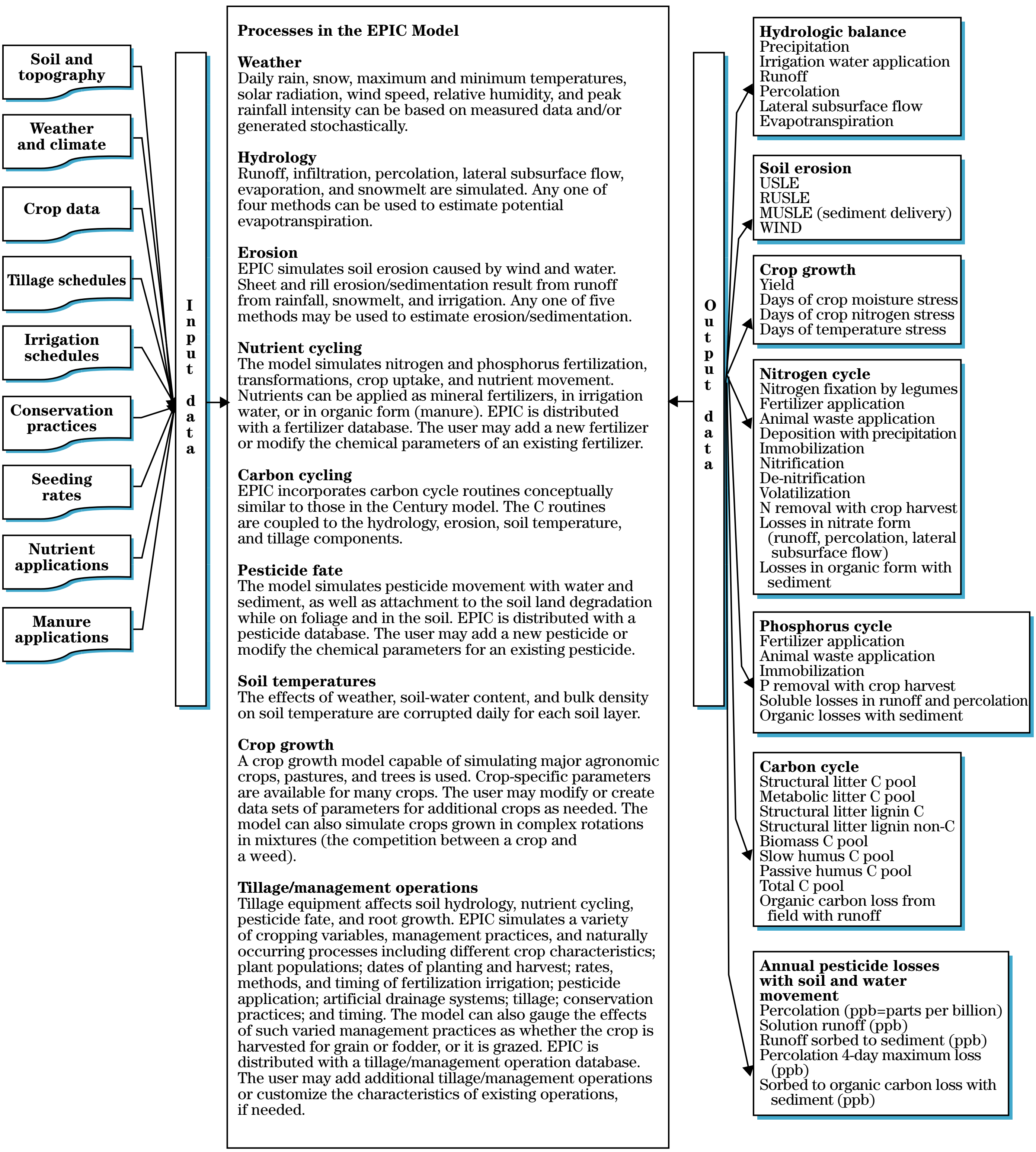


Table 1 EPIC-generated variables for NRI cropland sample points

Model component	Description	Reporting unit: Per acre	Reporting unit: Total
Hydrology	Precipitation		in
Hydrology	Irrigation water applied		in
Hydrology	Evapotranspiration		in
Hydrology	Surface water runoff		in
Hydrology	Percolation		in
Hydrology	Subsurface lateral flow		in
Soil erosion	Water erosion, sheet and rill (USLE)	ton	ton
Soil erosion	Water erosion, sediment delivery (MUSLE)	ton	ton
Soil erosion	Wind erosion	ton	ton
Nitrogen cycle	Commercial nitrogen fertilizer applied	lb	ton
Nitrogen cycle	Manure nitrogen applied	lb	ton
Nitrogen cycle	Total nitrogen applied	lb	ton
Nitrogen cycle	Nitrogen fixation	lb	ton
Nitrogen cycle	Nitrogen added with rainfall	lb	ton
Nitrogen cycle	Nitrogen volatilized	lb	ton
Nitrogen cycle	NO_3 loss in runoff	lb	ton
Nitrogen cycle	NO_3 lost in leachate	lb	ton
Nitrogen cycle	NO_3 loss in subsurface lateral flow	lb	ton
Nitrogen cycle	Organic nitrogen loss with waterborne sediment	lb	ton
Nitrogen cycle	Organic nitrogen loss with windborne sediment	lb	ton
Nitrogen cycle	Sum of all nitrogen losses	lb	ton
Phosphorus cycle	Commercial phosphorus fertilizer applied	lb	ton
Phosphorus cycle	Manure phosphorus applied	lb	ton
Phosphorus cycle	Total phosphorus applied	lb	ton
Phosphorus cycle	Soluble phosphorus lost in runoff	lb	ton
Phosphorus cycle	Soluble phosphorus lost in leachate	lb	ton
Phosphorus cycle	Organic phosphorus loss with waterborne sediment	lb	ton
Phosphorus cycle	Organic phosphorus loss with windborne sediment	lb	ton
Phosphorus cycle	Sum of all phosphorus losses	lb	ton
Carbon cycle	Soil organic carbon (30-yr average)	ton	ton
Carbon cycle	Soil organic carbon (change over 30 yr)	ton	ton
Carbon cycle	Beginning soil organic carbon (yr 1)	ton	ton
Carbon cycle	Ending soil organic carbon (yr 30)	ton	ton
Other	Crop yield	Varies by crop	

Summary of crops and cropland acres included in the study

The domain of the NNLSC database was derived from the 1997 NRI. It includes NRI sample points with one of the following 13 crops recorded for 1997: corn, soybeans, wheat, cotton, barley, sorghum, rice, potatoes, oats, peanuts, legume hay, grass hay, and mixed legume-grass hay. Some crops such as summer fallow, tobacco, sugar beets, and sunflowers were not included because of the lack of information on farming activities from farmer surveys. In cases where the NRI crop classification scheme grouped several crops into a single group—such as other row crops, other close grown crops, other vegetable crops, and other crops—it was not possible to link farmer survey data on specific crops to the NRI points.

In the West, the domain was further restricted to include only the major agricultural areas. The western areas were delineated by 6-digit Hydrologic Unit Code (HUC) watersheds, and 19 were selected to represent cropland in the West. The selected areas consisted of 105 8-digit HUCs. Hawaii, Alaska, and United States territories were not included.

The total number of 1997 NRI sample points in the domain was 178,567. This coverage accounts for approximately 298 million acres, representing about 80 percent of the 377 million acres of cropland in the United States as estimated by the NRI for 1997 (tables 2 and 3). Map 2 shows the percentage of cropland acres that were included in the study. Approximately 92 percent of the NRI acreage for the 13 crops was included in the domain; acres of these crops not included were largely in the West. Over 98 percent of the NRI acres are represented in the domain for six crops—corn, sorghum, soybeans, cotton, peanuts, and rice. Map 3 shows the dominate crops for each of the seven regions.

Not all areas of the country are well represented by the 13 crops. Areas where summer fallow, tobacco, sugar beets, sunflowers, specialty crops, orchards, and vegetable crops are dominant crops are not covered in this study. Only about 18 percent of the cropland acreage in Florida is represented, mostly in northern Florida (table 3, map 2). Seven western states (Arizona, California, Nevada, Oregon, Utah, Washington, and Wyoming) are also poorly represented, with only about 26 percent of the cropland acreage included overall. Three New England states (Massachusetts, New Hampshire, and Rhode Island) had only 34 percent of the cropland included.

To properly account for management factors, it was necessary to break down NRI corn acres into corn for grain and corn for silage, and break down NRI wheat acres into winter wheat and spring wheat. County proportions for each of the crop breakdowns were obtained from the 1997 Census of Agriculture. For example, consider an NRI wheat point representing 2,600 acres in a county where 60 percent of the wheat was winter wheat and 40 percent was spring wheat. This point would be replaced with a winter wheat point with 1,560 acres and a spring wheat point with 1,040 acres. All other attributes of the original NRI point were assigned to each of the two derived points. Corn for grain, corn for silage, winter wheat, and spring wheat were set up as separate URUs for modeling. (number of points totaled 222,358 after the break down of corn and wheat).

Legume hay and mixed legume-grass hay were treated as the same crop as it was assumed they would both be managed as legume hay. Both were included in the same URU.

Table 2 Percent of NRI cropland acres included in the study–by crop

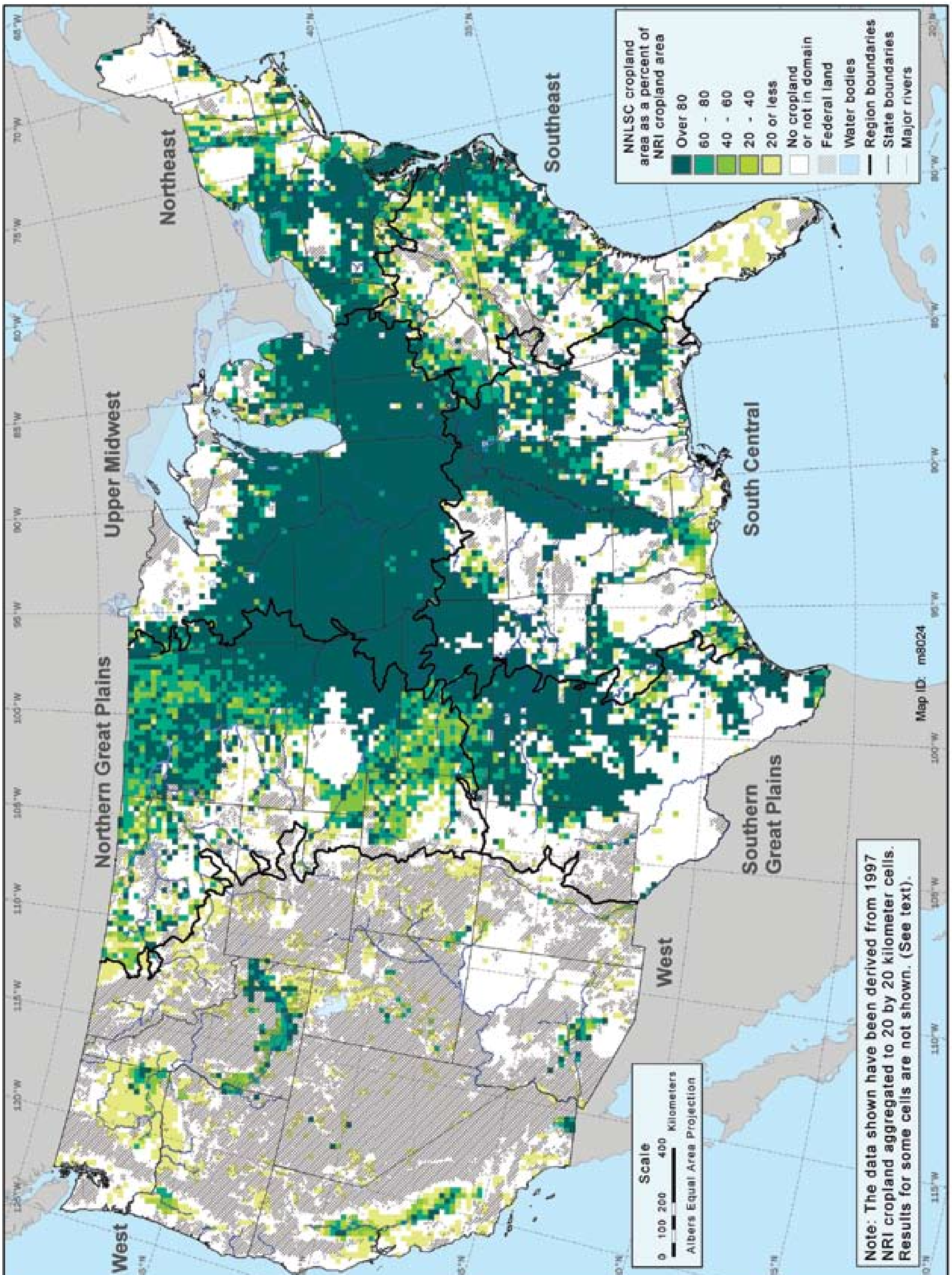
	1997 NRI*		Domain of the NNLSC database		
Crop	**Number of NRI sample points**	**Acres (1,000s)**	**Number of NRI sample points**	**Acres (1,000s)**	**Percent NRI acres included in domain**
Corn	56,285	84,549,200	55,105	83,416,000	98.7
Sorghum	5,502	10,972,600	5,406	10,897,300	99.3
Soybeans	45,379	67,767,600	45,039	67,542,800	99.7
Cotton	8,423	17,095,400	8,182	16,858,200	98.6
Peanuts	1,119	1,874,600	1,089	1,843,400	98.3
Potatoes	915	1,247,400	688	986,700	79.1
Tobacco	913	1,386,600	0	100	0.0
Sugar beet	742	1,228,800	0	0	0.0
Sunflowers	1,275	2,405,900	0	0	0.0
Other row crops	1,446	2,027,200	0	0	0.0
Other vegetable crops	2,691	3,990,900	0	0	0.0
Wheat	33,774	70,280,000	31,319	65,517,100	93.2
Oats	2,241	3,960,800	2,036	3,772,400	95.2
Rice	1,929	3,664,400	1,913	3,637,300	99.3
Barley	3,252	5,895,400	2,384	4,634,900	78.6
Other close-grown crops	3,077	6,040,200	0	0	0.0
Grass hay	14,094	21,500,500	9,447	14,596,300	67.9
Legume hay	9,986	14,982,700	6,879	10,980,400	73.3
Mixed hay	12,925	19,626,500	9,080	13,795,200	70.3
Summer fallow	7,663	20,677,600	0	0	0.0
Horticulture (fruits, nuts, berries, etc.)	4,477	6,458,600	0	0	0.0
Other crops	5,548	9,365,000	0	0	0.0
All crops	223,656	376,997,900	178,567	298,478,000	79.2

* Includes both cultivated and non-cultivated crop categories

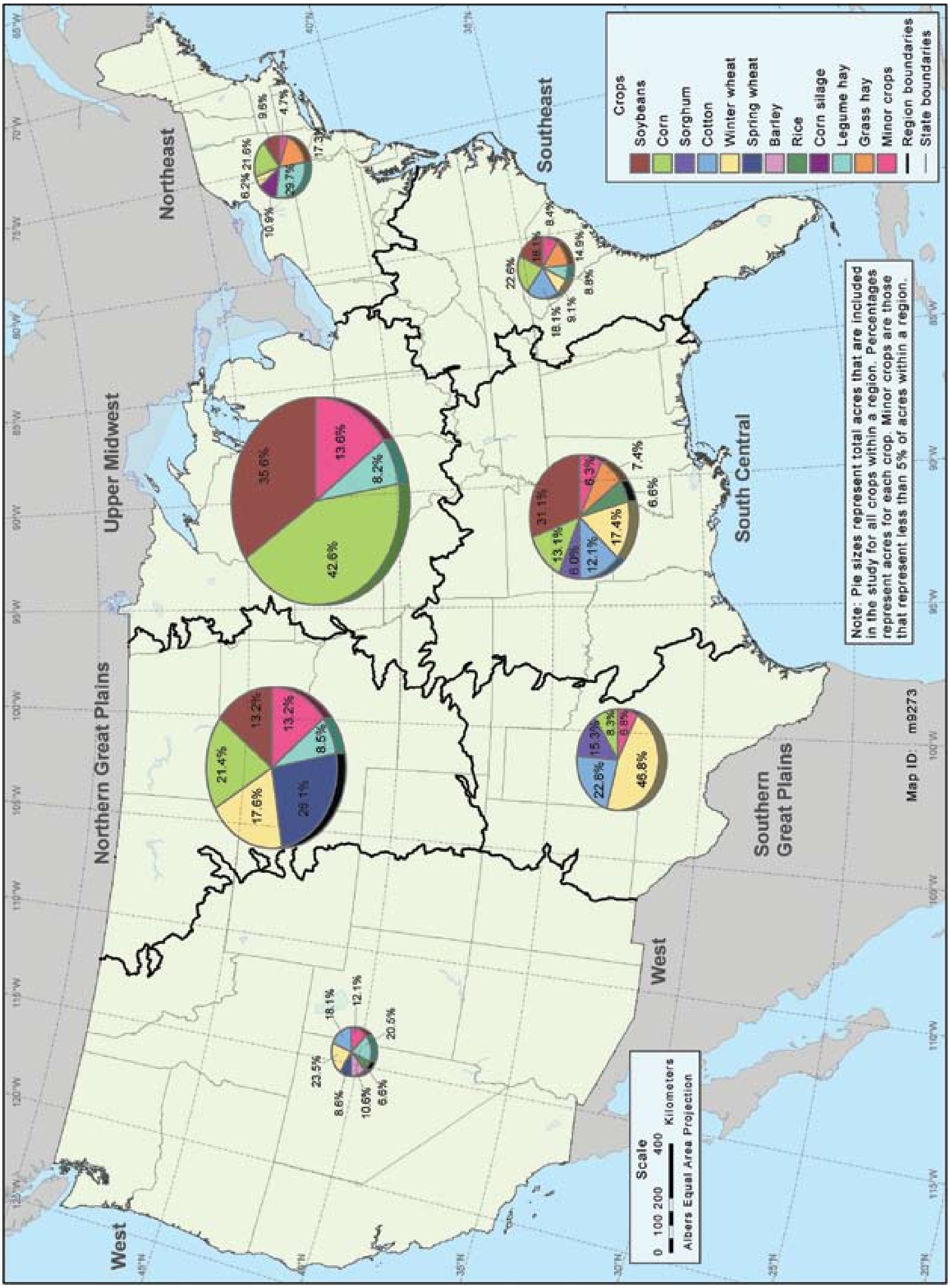
Table 3 Percent of NRI cropland acres included in the study–by state

State	1997 NRI		Domain of the NNLSC database		
	Number of NRI sample points	Acres (1,000s)	Number of NRI sample points	Acres (1,000s)	Percent NRI acres included in domain
Alabama	1,954	2,954	1,620	2,440	82.6
Arizona	1,004	1,212	284	439	36.2
Arkansas	3,986	7,625	3,837	7,375	96.7
California	4,844	9,635	1,560	3,566	37.0
Colorado	4,150	8,770	1,889	4,611	52.6
Connecticut	201	204	106	119	58.1
Delaware	504	485	459	448	92.5
Florida	1,659	2,752	283	497	18.1
Georgia	2,787	4,757	2,112	3,708	77.9
Hawaii	349	246	0	0	0.0
Idaho	4,737	5,517	2,451	2,683	48.6
Illinois	16,789	24,011	16,505	23,725	98.8
Indiana	9,751	13,407	9,391	12,961	96.7
Iowa	15,173	25,310	14,979	25,049	99.0
Kansas	13,595	26,524	11,404	21,115	79.6
Kentucky	4,132	5,178	3,432	4,343	83.9
Louisiana	2,453	5,659	1,535	3,793	67.0
Maine	294	413	147	248	60.1
Maryland	1,958	1,616	1,657	1,409	87.2
Massachusetts	256	277	94	106	38.3
Michigan	6,480	8,540	5,326	7,029	82.3
Minnesota	12,251	21,414	11,465	19,487	91.0
Mississippi	3,510	5,352	3,121	4,747	88.7
Missouri	9,202	13,751	8,571	12,680	92.2
Montana	4,254	15,171	1,795	7,215	47.6
Nebraska	11,434	19,469	10,230	17,073	87.7
Nevada	780	701	63	122	17.4
New Hampshire	149	134	46	39	29.2
New Jersey	661	589	363	327	55.5
New Mexico	1,640	1,875	841	1,107	59.0
New York	3,610	5,417	2,731	4,069	75.1
North Carolina	2,992	5,639	2,343	4,466	79.2
North Dakota	12,710	25,004	9,636	18,998	76.0
Ohio	8,958	11,627	8,373	10,945	94.1
Oklahoma	4,546	9,737	4,243	9,161	94.1
Oregon	2,475	3,762	398	610	16.2
Pennsylvania	4,493	5,471	3,867	4,776	87.3
Rhode Island	45	22	5	2	9.3
South Carolina	1,912	2,574	1,411	1,975	76.7
South Dakota	9,401	16,738	7,882	13,594	81.2
Tennessee	3,739	4,644	3,208	3,980	85.7
Texas	11,136	26,938	9,386	22,921	85.1
Utah	1,308	1,679	170	272	16.2
Vermont	624	607	394	359	59.1
Virginia	2,621	2,918	1,832	2,044	70.1
Washington	2,805	6,656	467	1,109	16.7
West Virginia	684	864	394	501	57.9
Wisconsin	6,468	10,613	5,851	9,597	90.4
Wyoming	1,500	2,174	410	643	29.6
Puerto Rico	692	368	0	0	0.0
All states	223,656	376,998	178,567	298,478	79.2

Map 2 Percent of cropland acres included in study



Map 3 Crop acreage–by region



Representing soil characteristics in the model

The soil's chemical and physical properties influence the movement of water, the cycling of nutrients and carbon, and crop growth. Soil is modeled in EPIC as a series of horizontal layers through which water and dissolved materials move through and which plant roots penetrate. The EPIC model uses information on the initial soil profile and soil properties (table 4). These are provided as inputs to the model or, if they are unknown, EPIC will estimate them. As the model simulation proceeds over several years, EPIC changes some of the soil properties in response to farming activities and weather. For example, the thickness of the surface layer decreases as soil is removed by erosion.

Soil data needed for the model were obtained from the NRCS Soil Survey databases linked to the NRI sample points. Soils represented by the NRI sample points were grouped into 2,688 soil clusters within which differences among soil properties would result in low variability among the major model output variables tracked in the study. For EPIC modeling, a single set of soil attributes was used to represent the NRI points in each of the 2,688 soil clusters (see box inset—Derivation of soil clusters).

For analysis and presentation of results, the 2,688 soil clusters were categorized into 25 groups defined by the combination of two variables—soil surface texture and hydrologic soil group. Surface texture was used to classify each soil into one of the following seven texture groups: coarse, moderately coarse, medium, moderately fine, fine, organic, and other. The coarse texture group consisted of soils with sandy surface textures including: coarse sand, sand, fine sand, very fine sand, loamy coarse sand, loamy sand, loamy fine sand, and loamy very fine sand. The moderately coarse texture group included soils with coarse sandy loam, sandy loam, and fine sandy loam surface textures. Medium textured soils were classified as those having very fine sandy loam, loam, silt loam, and silt surface textures. The moderately fine group included soils with clay loam, sandy clay loam, and silty clay loam surface textures. Fine textured soils were classified as those with sandy clay, silty clay, and clay surface textures. Peat and muck soils were classified as organic. Remaining soils were classified as other.

The hydrologic soil group is based on the NRCS classifications of soil runoff potential. Group A soils are primarily deep, well-drained sands or gravels having a low runoff potential and a high infiltration rate. Group B soils are moderately deep to deep soils with moderate infiltration rates when thoroughly wetted. Group C soils have slow infiltration rates when thoroughly wetted, sometimes with a soil layer impeding downward movement of water. Group D soils have a high runoff potential and a very slow infiltration rate when wet; these are soils with a high swelling potential, soils with a permanent high water table, or shallow soils over nearly impervious material.

Nearly 30 percent of the NRI cropland acres included in the study are classified as medium textured hydrologic soil group B soils (table 5). Soils with medium texture and hydrologic soil group C accounted for 17 percent, and soils with moderately fine texture and hydrologic soil group B accounted for 16 percent. The remaining 22 soil groupings accounted for 37 percent of the acres.

Table 4 Soil characteristics data required by EPIC

Soil attributes for each soil layer	Other soil attributes
Layer depth (m)	Number of soil layers
Bulk density (moist—ton/m^3)	Maximum number of layers
Bulk density (dry—ton/m^3)	Soils 5 ID
Water content at wilting point (1,500 KPA) (m/m)	Map unit symbol
Water content at field capacity (33 KPA) (m/m)	Hydrologic soil group (A,B,C,D)
Sand content (%)	Initial splitting thickness (m)
Silt content (%)	Weathering code
pH	Albedo (wet)
Sum of bases (cmol/kg)	Minimum profile thickness (m)
Organic carbon (%)	Minimum thickness of maximum layer (m)
Organic nitrogen concentration (g/ton)	Minimum depth to water table (m)
Calcium carbonate (%)	Maximum depth to water table (m)
Cation exchange capacity (cmol/kg)	Initial depth to water table (m)
Coarse fragment content (% volume)	Sub-surface flow travel time (mm/h)
Nitrate concentration (g/ton)	Initial ground water storage (mm)
Labile phosphorus concentration (g/ton)	Maximum ground water storage (mm)
Crop residue (ton/ha)	Runoff curve number (0–100)
Phosphorous sorption ratio	Return flow fraction of water percolating through root zone
Saturated conductivity (mm/h)	No. years of cultivation at start
Fraction of storage interacting with NO_3 leaching (g/ton)	Initial soil water content (% of field capacity)

Derivation of soil clusters

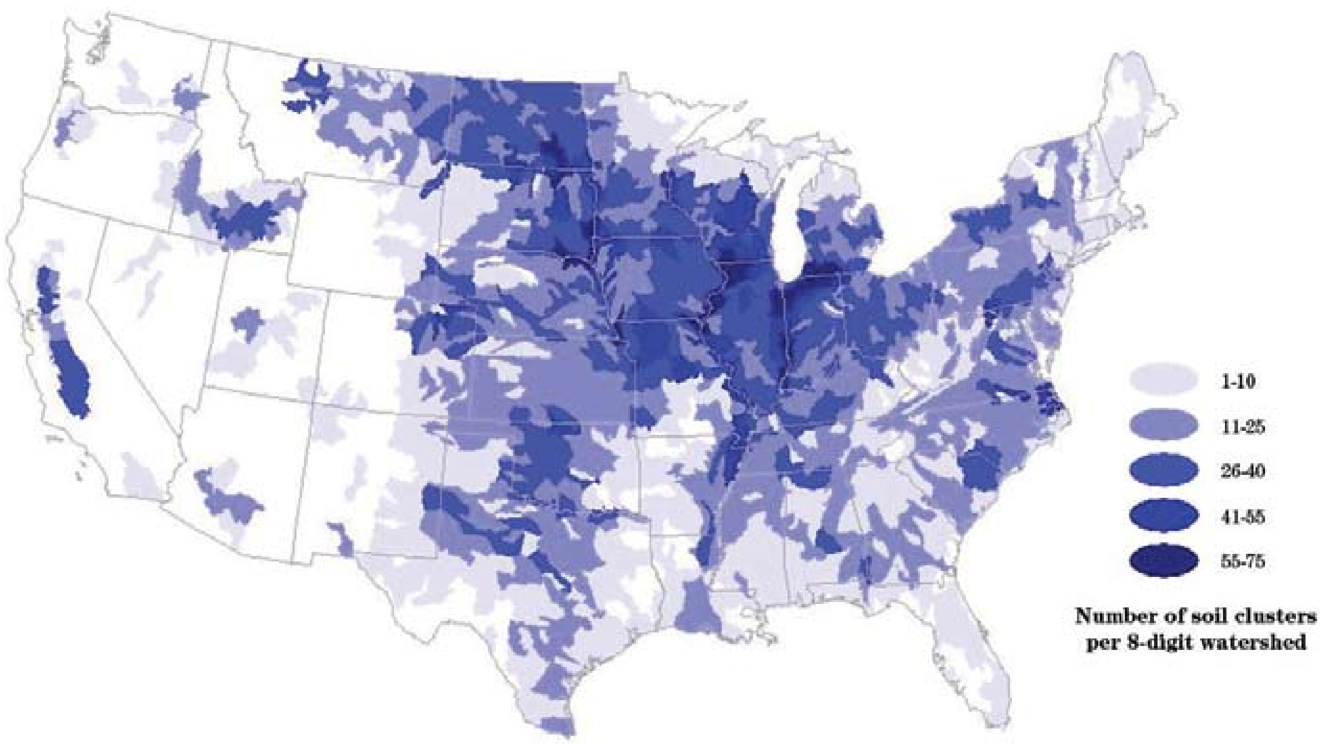
A statistical clustering procedure was used to define soil clusters with similar attributes (Sanabria and Goss 1997; Goss et al. 2001). Soil attribute data were obtained from soil characteristics defined for each of the NRI cropland sample points.

The clustering procedure was conducted using 27 soil attributes that are important for estimation of erosion and nutrient and carbon cycling. The soil attribute data were standardized to a mean of zero and a standard deviation of one prior to clustering to prevent attributes with large values from dominating the procedure. A factor analysis summarized the correlations and interactions of the properties into several underlying factors. Then each state's soils were clustered into groups of soils having similar factors using Ward's (1963) method in SAS (Statistical Analysis Software). This process placed a number of soils with similar properties into one cluster. Finally, the soil having the multivariate mean closest to the multivariate mean of the group was selected to represent the group. If the selected soil had peculiar properties, such as a very shallow depth, the next closest soil was used. The clustering procedure identified 2,688 soil clusters that represented all of the NRI cropland points included in the study.

The 2,688 soil clusters are not co-located spatially and include both dominant soils and relatively minor soils. A particular soil cluster could be found in several different watersheds in various locations throughout the United States. Some regions of the country have more diverse soils than other regions and, therefore, will have more soil clusters represented. As shown in figure 3, the number of soil clusters in watersheds defined by 8-digit HUCs can vary from less than 7 to as many as 75.

A specific example of the diversity of soils represented in the modeling is shown in figure 4, where the percentage of each soil cluster is presented for two watersheds in Iowa. Many of the soil clusters are found in both watersheds. In the Lower Iowa watershed (8-digit HUC 10230002), 31 different soils are represented. These 31 soils included three dominant soils, each representing more than 10 percent of the NRI cropland acreage in the watershed, and 28 relatively minor soils, each representing less than 7 percent of the acreage. The Floyd watershed (8-digit HUC 07080209) has 18 soils with 3 dominant soils and 15 minor soils. As will be shown later in the report, relatively minor soils can sometimes make a significant contribution to estimates of soil and nutrient loss from farm fields within a watershed.

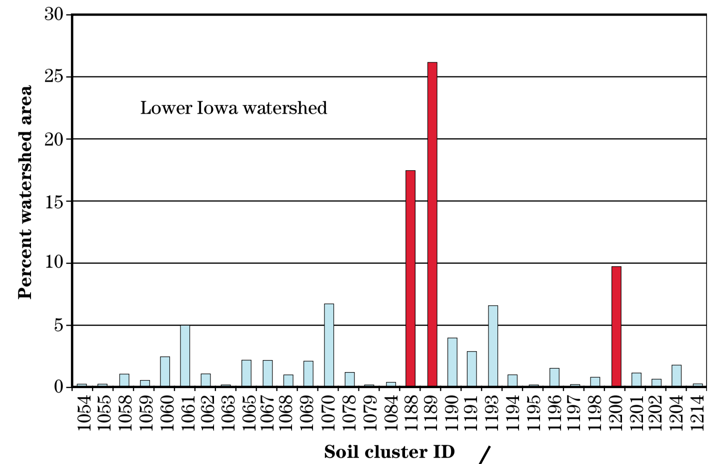
Figure 3 Number of soil clusters in each 8-digit watershed



Note: White areas have no cropland or no NRI cropland sample points in the domain.

Figure 4 Diversity of soils represented in the model for two IA watersheds (dominant soils are colored red)

Soil cluster	Representative soil	Texture group	Hydrologic soil group	Soil cluster	Representative soil	Texture group	Hydrologic soil group
1054	Fairhaven	Medium	B	1189	Lagoda	Medium	B
1055	Kossuth	Moderately fine	B	1190	Sharpsburg	Moderately fine	B
1056	Alton	Moderately fine	C	1191	Adair	Medium	C
1057	Galva	Moderately fine	B	1192	Kenyon	Medium	B
1058	Hoopeston	Moderately coarse	B	1193	Marshall	Moderately fine	B
1059	Coland	Moderately fine	B	1194	Sparta	Coarse	A
1060	Tama	Medium	B	1195	Huntsville	Medium	B
1061	Coppock	Medium	B	1196	Downs	Medium	B
1062	Shelby	Moderately fine	B	1197	Village	Medium	B
1063	Turlin	Medium	B	1198	Lineville	Medium	C
1065	Fayette	Medium	B	1200	Humeston	Medium	C
1067	Nodaway	Medium	B	1201	Lamoni	Fine	C
1068	Gara	Medium	C	1202	Wabash	Moderately fine	D
1069	Lindley	Medium	C	1203	Terril	Medium	B
1070	Colo	Moderately fine	B	1204	Floyd	Medium	B
1074	Ida	Medium	B	1207	Monona	Medium	B
1078	Adair	Moderately fine	C	1209	Racine	Medium	B
1079	Lamont	Moderately coarse	B	1212	Spicer	Moderately fine	B
1084	Dickinson	Moderately coarse	B	1214	Chelsea	Coarse	A
1188	Ely	Medium	B				



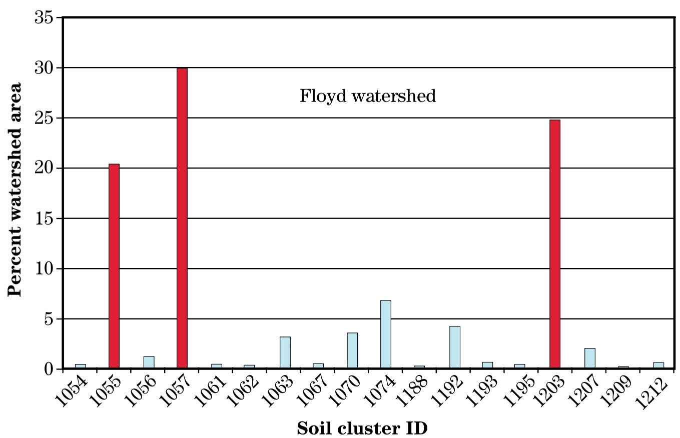


Table 5 Representation of 25 soil groups in cropland acres included in the study

Soil texture group	Hydrologic soil group	Number of soil clusters	Number of NRI sample points in soil clusters	Acres (1,000s)	Percent
Fine	B	8	310	300	0.1
Fine	C	25	1,988	2,715	0.9
Fine	D	128	7,694	14,935	5.0
	All	161	9,992	17,950	6.0
Moderately fine	B	132	27,216	46,690	15.6
Moderately fine	C	154	9,587	17,554	5.9
Moderately fine	D	110	7,229	14,005	4.7
	All	396	44,032	78,249	26.2
Medium	A	15	326	474	0.2
Medium	B	719	53,238	88,353	29.6
Medium	C	418	33,594	50,530	16.9
Medium	D	178	8,641	14,127	4.7
	All	1,330	95,799	153,484	51.4
Moderately coarse	A	24	696	1,257	0.4
Moderately coarse	B	293	14,785	25,062	8.4
Moderately coarse	C	120	2,956	4,469	1.5
Moderately coarse	D	40	811	1,665	0.6
	All	477	19,248	32,452	10.9
Coarse	A	145	4,938	8,724	2.9
Coarse	B	68	2,907	5,066	1.7
Coarse	C	36	761	1,218	0.4
Coarse	D	3	101	145	<0.1
	All	252	8,707	15,152	5.1
Organic	A	26	522	755	0.2
Organic	B	17	121	189	<0.1
Organic	C	3	37	72	<0.1
Organic	D	11	78	126	<0.1
	All	57	758	1,142	0.4
Other	B	11	21	31	<0.1
Other	C	2	2	3	<0.1
Other	D	2	8	15	<0.1
	All	15	31	49	<0.1
Totals	All	2,688	178,567	298,478	100.0

Representing weather in the model

Daily weather including precipitation volume, minimum and maximum temperatures, solar radiation, wind speed and prevalent direction, and relative humidity are necessary to run the EPIC model. Measured data can be input or the model can stochastically generate daily weather from the input of long-term monthly climate statistics. For this study, the weather generator option was used. The weather generator requires the average historical monthly maximum half hour rainfall and days per month with precipitation, which were derived from the EPIC climatic dataset. Thus, while the daily weather data used in this study are not actual weather, the simulated weather data are representative of historical weather patterns.

The weather generator, which is part of the EPIC model, operates stochastically. The estimate for precipitation involves two steps. First, the probability of precipitation is determined by using a random number generator to output a point between 0 and 1, which is then compared to the appropriate wet-dry probability distribution derived from climate records. If the random number is less than or equal to the wet-dry probability, precipitation occurs on that day. Secondly, the estimated precipitation is generated from a skewed normal daily precipitation distribution. On any given day, the input must include whether the previous day was dry or wet since the model provides for a higher probability of a wet day following a wet day. Determining whether the precipitation is rain or snow is based on air and soil temperatures. As configured for these simulations, EPIC did not account for rainfall intensity (storm duration or frequency within the day) or the interception and surface storage of precipitation.

Daily maximum and minimum air temperatures and solar radiation are generated from a normal distribution. A continuity equation is incorporated into the generator to account for temperature and radiation variations caused by dry versus rainy conditions. Maximum air temperature and solar radiation are adjusted downward when simulating rainy conditions and upwards when simulating dry conditions. The adjustments are made so that the long-term generated values for the average monthly maximum temperature and monthly solar radiation agree with the input averages.

A model routine developed by Richardson and Wright (1984) is used in EPIC to generate daily mean wind speed and direction given the mean monthly wind speed. This model is based on a modified exponential equation.

The relative humidity model routine uses a triangular distribution to simulate the daily average relative humidity from the monthly average. As with temperature and radiation, the mean daily relative humidity is adjusted to account for wet-day and dry-day effects.

Climate zones were derived from long-term weather data at about 1,000 weather stations to identify areas of the country with similar weather. A total of 35 climate zones were identified for the region east of the Rocky Mountains using a statistical clustering procedure similar to that used to identify soil clusters (see box inset—Derivation of climate zones for cropland east of the Rocky Mountains).

The western states were excluded from the statistical clustering due to large climatic variations within the 8-digit watersheds, usually due to orographic effects including elevation changes or rain shadows. A total of 31 climate zones were selected to represent cropland in the West by matching cropland areas within each 8-digit watershed to the most representative weather station available. Selection criteria included similarities in the cropland area and the weather station in elevation and topography, land cover, first and last freeze dates, mean temperatures and precipitation, and RUSLE rainfall erosivity. In most cases, a selected weather station represented cropland in several 8-digit watersheds.

The 66 climate zones are shown in map 4. Climate zones generally represent contiguous regions. There are some cases, however, where the climate clustering procedure identified similar climates in different regions of the country. These were grouped together into a single climate zone for purposes of EPIC modeling.

In each climate zone, a single weather station was selected to represent weather for EPIC model simulations. The selected weather station is also shown in map 4 and defined further in table 6. The weather statistics required by EPIC were derived from the weather records for the 66 selected weather stations. Solar radiation is estimated based on the latitude of the selected weather station. Wind speed and prevalent di-

rection are based on long-term monthly averages for the weather station. Precipitation and temperature are based on the monthly statistics for the weather station.

Because multiple EPIC model runs were made for each URU to represent different management activities, and multiple URUs within a climate zone were used to represent different crops and soils, it was necessary to generate the same weather for all model runs conducted for a given climate zone. To accomplish this, the weather generator was set to start from the same random number seed in the initial year of the simulation for all model runs done in each climate zone. The stochastically generated weather sequences (precipitation, wind, and temperature events) for a given climate zone are independent of those for all other climate zones. Thus, the weather simulation does not capture a large storm as it moves across several climate zones. The weather station data are, however, usually correlated with nearby weather stations, so that the general spatial trends in weather are well represented.

Derivation of climate zones for cropland east of the Rocky Mountains

For cropland areas east of the Rocky Mountains, a statistical clustering procedure was used to define areas with similar weather (Goss et al. 2001). Climate records for approximately 680 weather stations were analyzed using a statistical clustering procedure, resulting in identification of 35 climate clusters for this region. All climate clusters were delineated by a collection of 8-digit HUC watersheds.

Ten variables were used in the clustering procedure: mean monthly precipitation, mean standard deviation of monthly precipitation, mean monthly maximum half hour precipitation (intensity), mean monthly dew point, mean monthly maximum temperature, mean monthly minimum temperature, mean monthly solar radiation, mean number of monthly rain days, mean percentage of wet days followed by dry days, and mean percentage of wet days followed by wet days. In addition to the annual variables, variables were constructed for each of four seasons: December to February, March to May, June to August, and September to November. In all, there were 50 climate variables. To reduce the impact of unusually high or low values, all variables were standardized to a mean of zero and a standard deviation of one prior to clustering.

The set of variables was processed with a multivariate factor analysis and one or more strongly weighted variables were chosen from each factor. These variables were: the monthly dew point for each season, mean monthly maximum and minimum temperature, and average standard deviation of the monthly precipitation and mean monthly precipitation. Also selected were mean monthly solar radiation for the spring and winter and mean and standard deviation of the annual precipitation. The number of climate clusters was optimized using a breakpoint determined by the improvement in the sum of deviations from the mean.

Selecting a weather station from each cluster that has characteristics best representing all the weather stations in the cluster was done by identifying the weather station with the lowest sum of the standardized absolute value of all the variables (the weather station with variable values most like the average over all the weather stations in the cluster).

Map 4 Climate zones used for model simulations

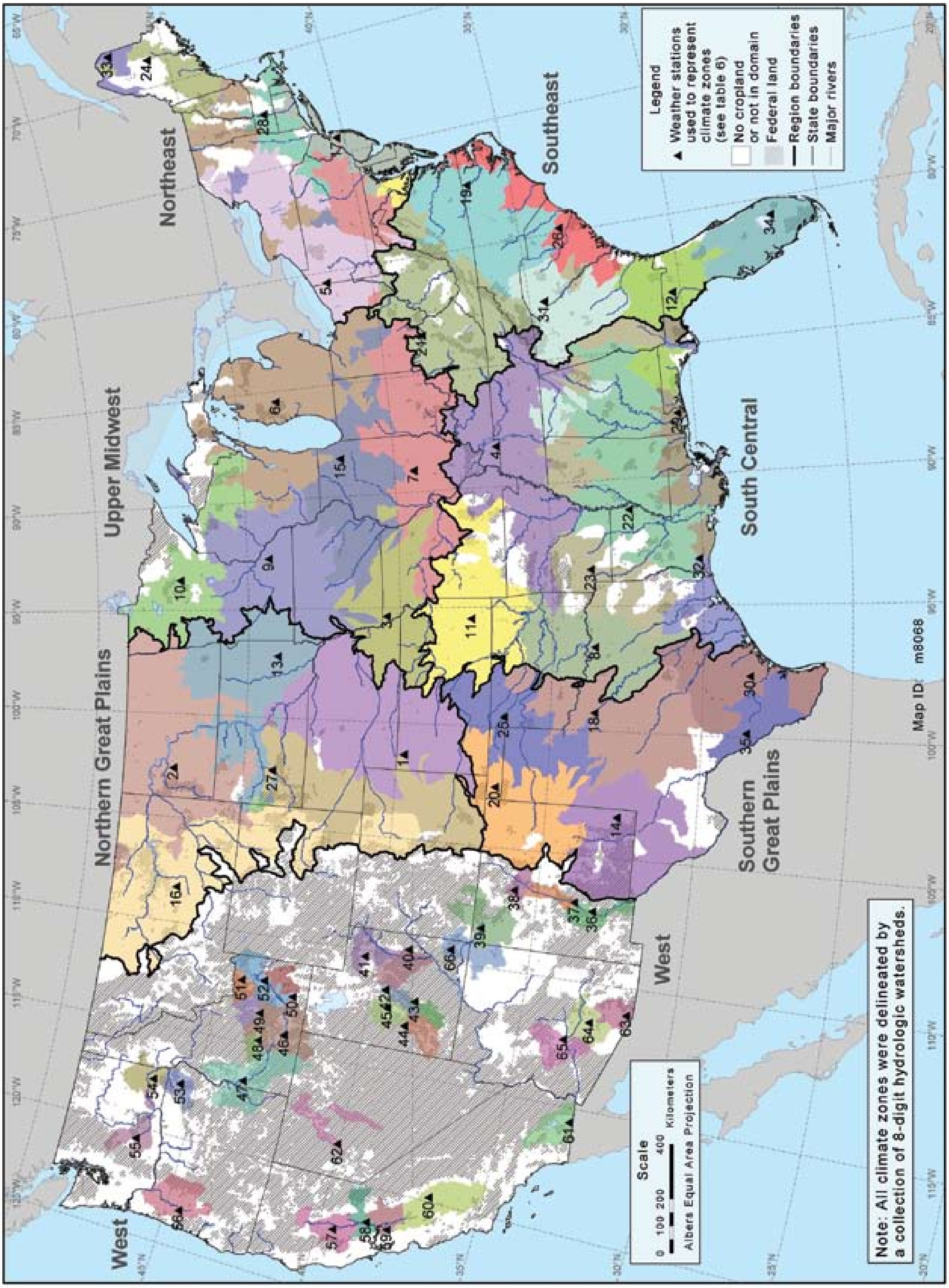


Table 6 Weather stations used to represent climate zones

Climate zone	Weather station name*	Percent of acres included in study
1	McDonald	7.3
2	Dunn Center	6.5
3	Tarkio Airport	5.4
4	Murray	5.6
5	Jamestown	2.1
6	Big Rapids Waterworks	6.4
7	Pana	8.7
8	Sherman	1.1
9	Zumbrota	8.7
10	Pokegama Dam	1.1
11	Chanute Airport	3.5
12	Live Oak	0.7
13	Madison Research Farm	6.7
14	Pearl	1.1
15	Aurora College	8.7
16	Flatwillow	2.2
17	Freehold	0.6
18	Seymour	3.1
19	Jackson	1.7
20	Boise City	1.9
21	Vanceburg Dam	1.0
22	Tallulah	2.6
23	Hope	1.4
24	Millinocket	0.1
25	Fort Supply Dam	3.2
26	Kingstree	0.9
27	Wasta	1.6
28	Amherst	0.2
29	Robertsdale	0.3
30	Beeville	1.3
31	Anderson	0.7
32	Lake Charles WSO	0.4
33	Caribou Airport	0.1
34	Belle Glade Experiment Station	<0.1
35	Carrizo Springs	0.3
36	Elephant Butte Dam	<0.1
37	Bosque Del Apache	<0.1
39	Fruitland	<0.1
40	Thompson	<0.1
41	Altamont	<0.1
42	Moroni	<0.1
43	Koosharem	<0.1
44	Black Rock	<0.1
45	Oak City	<0.1
46	Twin Falls WSO	0.3
47	Deer Flat Dam	0.2
48	Fairfield	<0.1
49	Craters Of Moon Nat'l Monument	<0.1
50	Arbon	0.1
51	Dubois Experiment Station	<0.1
52	Idaho Falls Airport	0.3
53	Wallowa	<0.1
54	Pomeroy	0.3
55	Yakima Airport	0.1
56	Corvallis St Col	0.1
57	Willows	0.2
58	Sacramento Airport	0.1
59	Tracy Pumping Plant	0.1
60	Fresno Airport	0.7
61	El Centro	0.1
62	Lovelock Airport	<0.1
63	Tumacacori	<0.1
64	Eloy	0.1
65	Litchfield Park	0.1
66	Blanding	<0.1
	Total	100.0

* Map 4 shows the locations of weather stations.
Note: Cluster 38, Jemez Springs, has no cropland points in the domain used in the study and is not listed.

Representing topographic characteristics and field drainage in the model

EPIC simulates effects within the boundaries of a field with a homogenous soil having a uniform slope and is bounded horizontally by the edges of the field and vertically from the soil surface down through the soil profile to the bottom of the root zone. Slope and slope length data are available directly from the NRI. Each NRI sample point was visited in 1982 and the slope and slope length determined for purposes of estimating sheet and rill erosion. Additional sample points added to the sample frame after 1982 were also visited to obtain slope and slope length. Protocols for measuring the slope and slope length are described in USDA NRCS (1997b). Slope and slope length were represented in the EPIC model for each URU as the average of the NRI cropland sample points associated with each URU.

Information on field drainage, such as drainage ditches and tile drains, was not available for the 1997 NRI sample points. (Data on tile drains were available for some of the 1992 NRI sample points, but as it was not a complete data record, the information was not used in this study.) EPIC can simulate these features, but without data indicating the extent to which they occurred, field drainage could not be included in the model simulations. Thus, all sample points were assumed to be adequately drained. This was simulated in the EPIC model by manipulating the water table depths. Initial water table depth was set to 2 meters for soils with an initial depth less than 2 meters. Also, for soils in which the minimum of the maximum water table depth was less than 2 meters, the minimum depth was set to 2 meters and the maximum depth was set to 3 meters.

Representing crop growth characteristics in the model

The crop growth model in EPIC is capable of simulating agronomic crops, pasture, and trees.

A single crop growth model is used in EPIC for simulating all 15 crops included in the study. However, each crop is uniquely characterized by over 50 parameters, listed in table 7. These crop growth parameters have been developed by scientists and model developers and are maintained as a database associated with the EPIC model.

Plant growth is simulated with a daily heat unit system that correlates plant growth with temperature. Accumulated heat units drive potential growth, and actual growth is reduced from potential growth by accounting for factors that constrain plant growth, including temperature, solar radiation, soil moisture, soil aeration, soil strength, and plant available nitrogen and phosphorus.

EPIC can simulate growth for both annual and perennial crops. Annual crops grow from planting date to harvest date or until the accumulated heat units equal the potential heat units for the crop. Perennial crops, such as alfalfa hay, maintain their root systems throughout the year, although they may become dormant after frost. In EPIC, a crop starts growing when the average daily air temperature exceeds the base temperature for the crop.

In addition to crop growth parameters, EPIC requires that the actual plant population be entered in plants per square meter. Plant population inputs vary from crop to crop and from state to state. Most available data from which plant population could be derived is for seeding rates. Conversion of seeding rates to plant population data requires information on seed germination and seedling survival rates. Since seeding rates are typically in units of volume or weight per acre, additional information was required on seed count per volume or weight, which varied to some extent across different regions of the country. For the majority of crops, seeding rate data were taken from the Cropping Practice Survey (1990–95) for both dry and irrigated production for each state (USDA ERS 2000). Data on seeds per pound, expected germination rates, and seedling survival were taken from Martin et al. (1976) and other published sources. Plants per square meter were estimated from these data sources for each crop and state for EPIC model input. Corn for grain values were used for corn silage. Plant populations for hay crops were set at the EPIC default levels. Barley and oat plant populations were assumed to be similar to spring wheat. The plant population calculation for cotton was based on Martin et al. (1976).

For peanuts in Texas and Oklahoma, particularly for dryland production, the plant populations derived using this standard approach were too low. Further in-

Table 7 Crop growth parameters required by EPIC

Crop name and number	Biomass-energy ratio and biomass-energy ratio decline rate parameter
Minimum and optimal temperatures for plant growth	Maximum potential leaf area index
Fraction of growing season when leaf area declines and leaf area index decline rate parameter	First and second points on optimal leaf area development curve
Aluminum tolerance index	Maximum stomatal conductance
Critical aeration factor	Maximum crop height
Maximum root depth	Parameter relating CO_2 concentration to radiation use efficiency
Minimum value of C factor for water erosion	Fractions of nitrogen, phosphorus, potassium, and water in yield
Lower limit of harvest index	Pest (insects, weeds, and disease) factor
Seeding rate and seed cost	Price for grain yield
Nitrogen uptake parameter (N fraction in plant at emergence, 0.5 maturity, and maturity)	Phosphorus uptake parameter (P fraction in plant at emergence, 0.5 maturity, and maturity)
Potassium uptake parameter (K fraction in plant at emergence, 0.5 maturity, and maturity)	Wind erosion factors for standing live residue, standing dead residue, and flat residue
First and second points on frost damage curve	Parameter relating vapor pressure deficit (VPD) to radiation use efficiency
VPD value and threshold VPD	Fraction of root weight at emergence and maturity
Heat units required for germination	Price for field forage
Plant population for trees, crops, or grass	Water use to biomass
Yield salinity ratio	Salinity threshold
Lignin fraction at half-maturity and maturity	Fraction turnout or lint for picker and stripper cotton

vestigation indicated that the predominant peanut type grown in Texas and Oklahoma is Spanish peanuts, with Runner types also occupying some acreage (Brooks and Ali 1994; Sanford and Evans 1995). Seed counts per pound of seed for the three types are approximately 500 for Virginia, 700 for Runner, and 1,200 for Spanish (Martin et al. 1976). Yields consistent with published statistics for Oklahoma and Texas were achieved by setting the plant population at 35 plants per square meter for dryland and 38 plants per square meter for irrigated acres.

EPIC yields obtained during this study are compared to historical crop yield data in table 8. Historic crop yield estimates by state and crop for a 5-year period from 1995 to 1999 were obtained from the National Agricultural Statistics Service (NASS) for the comparison. These estimates vary from year to year, in part reflecting variability in weather conditions. Yield estimates from the EPIC model simulations represent 30-year averages derived from probabilistically generated weather. Even if a comparable long-term average could be obtained from the NASS yield data, the comparison would be flawed because of technological advancements (such as improvements in seed varieties) that have occurred over time, which are manifested as an upward trend in the observed yield data over time that is not related to weather.

Overall, the 30-year EPIC average yield corresponded reasonably well to the 5-year historic average yield for most crops. The EPIC average national yield was relatively high compared to the 5-year NASS yield for corn silage, soybeans, grass hay, and legume hay. The EPIC yield was relatively low for peanuts and potatoes. Some of the differences in yields for some states will be due to differences between actual weather and the simulated weather used in the EPIC model runs, particularly in regions with prolonged drought conditions during 1995 to 1999. Other yield differences may be explained in part by the continuous crop simulations used to generate the EPIC results; crops commonly grown in rotation with other crops would be expected to have different yields than those determined under the continuous cropping conditions represented by the model simulations.

Table 8 Comparison of EPIC crop yields to NASS reported crop yields

Crop	Yield unit	NASS 5-year average annual yield (1995–99)	EPIC 30-year average annual yield	Difference from NASS yield estimate	Percent difference from NASS yield estimate
Barley	bu/a	59	56	-3	-5.3
Corn	bu/a	127	128	1	0.4
Corn silage	tons/a	16	22	6	38.5
Cotton	lb/a	626	681	55	8.7
Oats	bu/a	58	64	6	9.6
Peanuts	1,000 lb/a	2.6	1.7	-0.9	-34.6
Potatoes	100 lb/a	352	267	-85	-24.2
Rice	1,000 lb/a	5.8	5.2	-0.6	-11.1
Spring wheat	bu/a	33	39	6	17.4
Sorghum	bu/a	66	73	7	9.9
Soybeans	bu/a	38	55	17	46.1
Winter wheat	bu/a	43	40	-3	-5.7
Grass hay	ton/a	2	3	1	63.4
Legume hay	ton/a	3	5	2	59.7

Representing field operations in the model

All field operations used in the production of a crop are required inputs to the EPIC model. These include planting, a variety of tillage operations, irrigation, commercial fertilizer applications, manure applications, and harvesting. A generic set of field operation schedules was developed for each crop and irrigation system.

The timing of the operations was automatically determined during the model run on the basis of accumulated heat units. Year-to-year temperature differences preclude assigning specific dates prior to running the model; planting during a warm spring should occur earlier than during a cool spring, for example. Heat units are calculated as the difference between the average of the daily maximum and minimum temperatures and a specified base or developmental threshold temperature. Prior to running EPIC, heat units necessary for planting and heat units required for crop maturity are determined for each crop in each climate zone. As the model runs, heat units are accumulated for each year and the ratio of accumulated heat units to the required heat units is used to determine plant and harvest dates. The timing of other field operations is scheduled relative to plant date or harvest date and converted into heat units.

The heat unit scheduling code (HUSC) has two timing scales. For the first timing scale, the total expected heat units for any year is the sum of all daily average temperatures above 32 degrees Fahrenheit, derived from long-term climate records. This timing scale is used to schedule the plant date and operations occurring prior to planting.

As soon as planting occurs, a second timing scale becomes the applicable timing mechanism. For this second timing scale, the total expected heat units shift to the number of heat units required for the crop to reach maturity from the time of planting. The heat units required for the crop to reach maturity are calculated prior to the model simulation for each crop and climate zone based on the latitude and elevation of the weather station. During the model run, crop maturity heat units are accumulated when the daily average temperature exceeds a crop-specific base temperature, or threshold temperature.

A threshold date is also set that must be reached before any operation can occur regardless of heat units. Both conditions—accumulated heat units and threshold date—must be met before a field operation is simulated in EPIC.

A hypothetical example is provided in table 9 for corn. The month and day are the earliest date that the operation is allowed to occur. According to the example, a field cultivation will be simulated after March 15 when 12 percent of the annual heat units have accumulated. Corn is planted after April 1 when 15 percent of the annual heat units have accumulated. Once the corn begins to grow, the schedule is based on the fraction of heat units required for crop maturity. In this exam-

Table 9 Hypothetical example of an operations schedule for corn that demonstrates heat unit scheduling

Month	Day	Percent of annual heat units accumulated (above 32 °F)	Percent of crop maturity heat units (above 46 °F for corn)	Field operation
3	15	12	NA	Field cultivation
4	1	15	NA	Plant
5	1	NA	20	Application of commercial fertilizer
6	1	NA	35	Row cultivation
8	1	NA	115	Harvest
1	5	NA	None used	Kill crop (dummy operation for model)

NA = Not applicable

ple, corn requires 1,400 heat units. Crop maturity heat units are accumulated when temperatures are above the base temperature of corn—46 degrees Fahrenheit. Commercial fertilizer application is simulated when the plant is at 20 percent of maturity in this example. Cultivation is simulated at 35 percent of maturity. The corn is harvested at 115 percent of maturity to allow for grain drying. The crop is then terminated to allow these operations to repeat for the next year's crop.

Using the heat unit scheduling routine, specific field operation schedules were created for each crop and irrigation system in each climate zone. Irrigation operations, commercial fertilizer applications, and manure applications were incorporated into the specific field operation schedules according to rules presented in sections of this report addressing those topics. An example of a specific field operation schedule used for irrigated corn in Nebraska in climate zone 27 is shown in table 10.

Representing tillage in the model

Tillage equipment is used in agriculture to prepare the field for planting, weed control, and for irrigation management. Conventional tillage includes primary and secondary tillage operations performed in preparing a seedbed for planting, and typically includes plowing, chiseling, and disking operations that buries plant residue remaining from the previous crop. Conservation tillage is a system of field operations that attempts to reduce soil manipulation, thereby increasing the amount of crop residue remaining on the soil surface.

Table 10 Example of a specific field operation schedule for irrigated corn in climate zone 27 in NE (URU 7462) with conventional tillage and fall application of nitrogen

Month	Day	Proportion of annual heat units (accumulated above 32 °F)	Proportion of crop maturity heat units (accumulated above 46 °F)	Action
1	1	0.01	NA	Turns auto irrigate function on (model operation)
4	22	0.07	NA	Disk
4	29	0.09	NA	Disk
5	5	0.1	NA	Field cultivate
5	6	0.11	NA	Irrigate 75 mm 1 wk prior to plant
5	13	0.13	0	Row plant corn; heat units to maturity=1420, water stress factor= 0.85, plant population= 6.56 plants m^{-2}
6	3	NA	0.12	Row cultivate
6	17	NA	0.23	Row cultivate
7	29	NA	1	Turns auto irrigate function off when crop reaches maturity
9	25	NA	1.15	Harvest crop
9	26	NA	1.15	Kill crop (model operation)
10	16	NA	1.24	Chisel
10	25	NA	1.25	Anhydrous ammonia application at 173 lb/a injected at 150 mm
11	20	NA	1.25	Disk

NA = Not applicable
Note: This schedule is repeated for each year of the simulation to simulate continuous cropping; thus, the post-harvest operations are in preparation for the next year's corn crop.

This provides some protection against the erosive actions of wind and water. No-till is a system whereby the crop is planted directly into a seedbed undisturbed since harvest of the previous crop, providing the maximum erosion protection.

Three tillage systems were simulated in EPIC model runs—conventional tillage, mulch tillage (representing conservation tillage), and no-till. These three tillage systems are incorporated into the model in the field operation schedules, which are specific to each crop, irrigation system, and climate zone. An example generic field operation schedule for the three tillage systems for corn for grain is as follows:

Conventional tillage:

1. Tandem disk 2 weeks after harvest of previous crop.
2. Chisel 3 weeks after harvest of previous crop
3. Tandem disk 3 weeks before planting
4. Tandem disk 2 weeks before planting
5. Field cultivator 1 week before planting
6. Plant
7. Row cultivation 3 weeks after planting
8. Row cultivation 5 weeks after planting
9. Harvest

Mulch tillage:

1. Chisel 3 weeks after harvest of previous crop
2. Tandem disk 2 weeks before planting
3. Field cultivator 1 week before planting
4. Plant
5. Row cultivation 4 weeks after planting
6. Harvest

No-till:

1. Plant (No-till plant dates were set about one week later than the other tillage systems to account for the lower soil temperatures typically associated with no-till.)
2. Harvest

Each piece of equipment is associated with a set of model input parameters that include: mixing efficiency of operation, a random roughness coefficient, tillage depth, ridge height and interval, furrow dike height and interval, fraction of soil compacted (based on tire and tillage width), fraction of plant population reduced by operation, and harvest efficiency. Using these parameters, EPIC calculates standing, surface, and buried crop residue amounts, the extent to which soil mixing occurs, and other related outcomes that effect hydrology and erosion.

In addition to the equipment parameters, three other model parameters were adjusted to better represent the effects of the three tillage systems. Manning's roughness coefficient, which reflects surface roughness effects by reducing overland flow velocities, was set as follows: conventional tillage=0.1; mulch tillage=0.2, and no-till=0.3. Also two cover management factor parameters were adjusted to represent each tillage system. The Water Erosion Cover Coefficient reduces the effect of increasing canopy or residue for controlling erosion and was set as follows: conventional tillage=0.5; mulch tillage=0.8, and no-till=1.0. The Minimum Water Erosion Cover Factor is the lower limit that the USLE C-factor can be for any day and was set as follows: conventional tillage=0.25; mulch tillage=0.15, and no-till=0.05.

All three tillage systems were simulated for each URU for eight crops—corn, corn silage, sorghum, soybeans, barley, oats, spring wheat and winter wheat. For cotton, peanuts, and rice, only conventional tillage and mulch tillage systems were simulated, and only conventional tillage was simulated for potatoes. Hayland was treated as no-till. In addition, no-till was not simulated for any crops where gravity irrigation was used because of the need for land forming tillage operations associated with gravity irrigation systems.

The frequency of occurrence of the three tillage systems is needed to determine the probability associated with each tillage option for calculation of the weighted average for model outputs assigned to NRI cropland points (app. A). This information was obtained from county data by crop from the Crop Residue Management Survey (CRMS) (CTIC 2001) for the year 2000. The CRMS dataset includes five tillage classes for each crop grown within a county, state, or region—no-till, ridge till, mulch till, reduced till (15–30% residue), and conventional till (<15% residue). For

this study, conventional till included both the CRMS reduced till and the CRMS conventional till to represent residue amounts of 30 percent or less. In addition, the CRMS ridge till and mulch till categories were combined. The percentage of each of the three tillage systems simulated in this study was then obtained for each NRI cropland point and each URU using the CRMS county data.

The extent to which the 3 tillage systems are represented in the NNLSC database is summarized in table 11. The percentage representation for each tillage type varies by region and crop. Overall, however, model simulation results represent conventional tillage on about 55 percent of the acres, mulch tillage on about 17 percent of the acres, and no-till on about 28 percent of the acres (including hayland).

A subset of the full database was used to assess how accounting for conservation tillage effected model estimates of sediment loss, wind erosion, nitrogen loss, and phosphorus loss. This tillage comparison subset of model runs included only those URUs (and associated NRI sample points) where all three tillage systems were present. The tillage comparison subset consists of 565,673 model runs representing 207.6 million acres (70 percent of the acres included in the NNLSC database). Eight crops that were either non-irrigat-

Table 11 Representation of three tillage systems in the NNLSC database

	Acres (1,000s)	Percent conventional till	Percent mulch tillage	Percent no-till
By region				
Northeast	13,642	34.7	6.7	58.6
Southeast	13,394	52.9	7.5	39.5
South Central	45,350	63.2	13.3	23.5
Upper Midwest	112,581	45.9	19.4	34.7
Northern Great Plains	72,397	57.1	20.0	22.9
Southern Great Plains	32,096	77.4	16.4	6.3
West	9,018	62.6	13.1	24.3
By crop				
Barley	4,635	73.6	20.6	5.8
Corn	78,219	63.2	18.8	18.0
Corn silage	5,197	75.8	11.5	12.7
Cotton	16,858	87.9	12.1	0.0
Grass hay	14,596	0.0	0.0	100.0
Legume hay	24,776	0.0	0.0	100.0
Oats	3,772	72.5	20.2	7.3
Peanuts	1,843	94.5	5.5	0.0
Potatoes	987	100.0	0.0	0.0
Rice	3,637	89.0	11.0	0.0
Spring wheat	20,503	72.3	17.2	10.5
Sorghum	10,897	69.6	18.4	12.0
Soybeans	67,543	44.6	24.8	30.6
Winter wheat	45,014	69.1	19.8	11.1
All regions and crops	298,478	54.9	17.0	28.1

ed or sprinkler irrigated are included: corn, soybeans, sorghum, winter wheat, spring wheat, barley, oats, and corn silage.

Four sets of model results were constructed using the tillage comparison subset of model runs. A tillage-effects baseline representing the mix of tillage systems reported by CTIC (2001) was estimated. Acreage representation of the three tillage systems in this tillage-effects baseline is: 59 percent for conventional tillage, 21 percent for mulch tillage, and 21 percent for no-till (table 12). A set of alternative results was obtained for each of the three tillage systems as if all acres had been modeled using a single tillage system. Comparisons among these four sets of results are used in later sections of this report to assess the effects that tillage had on estimates of sediment loss, wind erosion, nutrient loss, and phosphorus loss in model simulations.

Representing conservation practices in the model

Three conservation practices, designed primarily to reduce sheet and rill erosion and sediment transport, were simulated—contour farming, stripcropping, and terraces. Contour farming is a technique in which farming operations such as tillage and planting are conducted along the contour of the field slope so that ridges are formed to slow overland runoff and trap sediment. Stripcropping is a technique for growing crops in a systematic arrangement of strips across a field such that no two adjacent strips are in an erosion-susceptible condition at the same time during the crop growing season, usually done by growing different crops in adjacent strips. A terrace is an engineered earth embankment, or a combination ridge and channel, constructed across the field slope, diverting water and intercepting concentrated runoff flows.

Table 12 Representation of tillage systems in the tillage-effects baseline

	Acres (1,000s)	Percent conventional tillage	Percent mulch tillage	Percent no-till
By region				
Northeast	6,034	62.5	14.3	23.2
Southeast	4,442	61.8	8.0	30.2
South Central	24,879	64.7	14.5	20.8
Upper Midwest	96,330	51.3	22.2	26.5
Northern Great Plains	56,551	64.6	21.5	13.9
Southern Great Plains	17,746	72.5	21.7	5.8
West	1,661	62.9	26.6	10.5
By crop				
Barley	3,256	75.0	17.8	7.2
Corn	71,016	62.9	18.0	19.1
Corn silage	4,082	74.1	12.7	13.2
Oats	2,078	69.0	20.9	10.1
Spring wheat	18,074	71.2	17.0	11.7
Sorghum	7,697	65.5	18.7	15.8
Soybeans	62,967	42.3	25.8	31.9
Winter wheat	38,473	68.6	19.7	11.7
All regions and crops	207,642	59.0	20.5	20.5

The NRI database provided information on which sample points had these three conservation practices and combinations of the practices. Separate URUs were created for each of three structural conservation practices as well as separate URUs for all combinations of practices. Overall, these three conservation practices were simulated for about 11 percent of the cropland acres included in the study (table 13). The most frequently occurring practice combination was terraces with contour farming, which represented about 5 percent of the acres.

In the EPIC model, the primary mode of simulating the effect of conservation practices on soil erosion is through manipulation of the support practice factor, or P-factor. An integral component of the equation used to estimate sediment loss, the P-factor is the ratio of soil erosion with a conservation practice like contouring, stripcropping, or terracing to soil erosion with straight-row farming up and down the slope. Conservation practices are always represented by a P-factor of less than 1.0 while a setting of 1.0 indicates no conservation practice. In addition, for some terraces slope length is reduced resulting in a shorter slope length and lower steepness (LS) factor. Within the NRCS curve number method for estimating runoff, there are provisions for reducing the curve number for fields with contouring, stripcropping, or terracing, resulting in reduced surface water runoff and more infiltration. The model recognizes conservation practice codes and automatically adjusts the NRCS curve number in the model.

The NRI provides estimates of the P-factor for all sample points including those with conservation practices and combinations of practices (USDA NRCS 1997b). These NRI estimates were used in the EPIC model simulations to represent the effects of the three conservation practices. The average values of the P-factor for the NRI cropland sample points associated with each URU were used as model inputs.

Additional model runs were conducted to assess the effects of the conservation practices on model estimates of sediment loss, nitrogen loss, and phosphorus loss. Two scenarios were established:

- A conservation-practice baseline scenario, consisting of the original model runs in the NNLSC database for all NRI sample points with one or more conservation practice.

Table 13 Representation of stripcropping, contour farming, and terraces in the NNLSC database

Conservation practice	Number of URUs	Number of NRI sample points in URUs	Acres (1,000s)	Percent acres
Terraces only	1,111	3,268	6,285	2.1
Terraces with contour farming	1,361	7,883	14,728	4.9
Terraces with stripcropping	0	0	0	0
Terraces with contour farming and stripcropping	28	31	64	<0.1
Contour farming only	1,165	3,728	5,965	2.0
Contour farming with stripcropping	462	1,183	1,764	0.6
Stripcropping only	531	1,308	2,930	1.0
None	20,592	161,166	266,741	89.4
Totals	25,250	178,567	298,478	100.0

- A no-practices scenario, consisting of the results of revised model runs where the P-factor was set equal to 1.0 and the practice code was set such that the NRCS curve number represented conditions without conservation practices. All other model settings were the same as in the conservation-practices baseline scenario, including slopes and slope lengths and tillage practices.

Outputs from the no-practices scenario model runs were aggregated in the same manner as for the conservation practice baseline model runs. The two scenarios represent the same acreage. To determine the effects of the conservation practices, outputs for the URUs with practices were compared to the same set of URUs simulated without practices. Since the P-factor is not part of the wind erosion equation, the effects of the three practices on wind erosion was not assessed.

Representing irrigation in the model

Irrigation was simulated for URUs representing NRI sample points with irrigation. Irrigated land, as defined for NRI purposes, is land that shows physical evidence of being irrigated during the year of the inventory (presence of ditches, pipes, or other conduits) or having been irrigated during two or more of the four years preceding the inventory (USDA NRCS 1997b). Three types of irrigation are recorded in the NRI: gravity irrigated, pressure irrigated, or gravity and pressure irrigated.

For EPIC modeling, sprinkler irrigation was used to simulate pressure systems and furrow/flood irrigation was used to simulate gravity systems. The gravity pressure irrigation type was defined in the NRI as cases where water was delivered to the field by gravity flow and then applied through a pressurized sprinkler system (USDA NRCS 1997b); this was modeled in EPIC as a sprinkler system. When simulating no-till, however, a sprinkler system was always used. For rice, flood/furrow irrigation was always used. For URUs with average slopes greater than 3 percent, only sprinkler irrigation was used for non-hay crops.

Since information about the timing and amount of irrigation water used was not available, a generic irrigation schedule was simulated. A manual irrigation of 75 millimeters (3 in) for gravity and 50 millimeters (2 in) for sprinkler systems was applied prior to planting to ensure adequate moisture for seed germination. Subsequent irrigation events were simulated using the automatic irrigation feature of EPIC to irrigate during the growing season. The plant growth stress factor in this routine was set at 0.85, which caused the model to irrigate on any day that plant growth was less than 85 percent of potential growth if all other parameter conditions were met. Other parameters were set to: only irrigate to field capacity when irrigation was triggered; never irrigate more frequently than once in 5 days; irrigate with volumes between 25 and 75 millimeters (1–3 in); never irrigate more than 900 millimeters annually (35 in); limit irrigation volumes at each application so that no more than 5 percent is lost to runoff for sprinkler systems and no more than 20 percent is lost to runoff for gravity systems.

Overall, about 13 percent of the acres included in the study were irrigated (table 14). In the West, however, 79 percent of the acres were irrigated. The Southern Great Plains and South Central regions also had significant irrigation; 28 percent and 21 percent of the cropland acres included in the study were irrigated in these two regions, respectively. About 15 percent of the acres in the Northern Great Plains region were irrigated. Irrigated acres in the Southeast region represented 6 percent of the cropland acres included in the study. The Northeast and Upper Midwest regions had very few irrigated acres.

Representing commercial fertilizer applications in the model

Commercial fertilizer application is a critical factor for determining the amount of nitrogen and phosphorus loss from farm fields. The timing of application, the method of application (whether the materials are incorporated into the soil at application or not), and the amount applied all have significant influences on EPIC model results. Farmer surveys typically collect information on the number of applications, the timing of application, the amount applied at each application, and the method of application for both nitrogen and phosphorus. However, reports published by NASS and ERS seldom include summary statistics with this much detail because sample sizes from farmer surveys are usually too small to report these results on an annual basis.

Table 14 Representation of irrigation in the NNLSC database

Region	Irrigation type	Number of NRI sample points	Acres (1,000s)	Percent acres
Northeast	Pressure/sprinkler	161	164	1.2
	Gravity	3	2	<0.1
	No irrigation	11,118	13,475	98.8
	Subtotal	11,282	13,642	100.0
Southeast	Pressure/sprinkler	491	821	6.1
	Gravity	8	11	0.1
	No irrigation	8,456	12,563	93.8
	Subtotal	8,955	13,394	100.0
South Central	Pressure/sprinkler	2,673	4,914	10.8
	Gravity	2,571	4,786	10.6
	No irrigation	22,221	35,650	78.6
	Subtotal	27,465	45,350	100.0
Upper Midwest	Pressure/sprinkler	1,237	1,991	1.8
	Gravity	278	490	0.4
	No irrigation	73,176	110,100	97.8
	Subtotal	74,691	112,581	100.0
Northern Great Plains	Pressure/sprinkler	3,147	6,112	8.4
	Gravity	2,563	4,525	6.3
	No irrigation	30,325	61,759	85.3
	Subtotal	36,035	72,397	100.0
Southern Great Plains	Pressure/sprinkler	3,009	6,707	20.9
	Gravity	1,222	2,322	7.2
	No irrigation	10,264	23,067	71.9
	Subtotal	14,495	32,096	100.0
West	Pressure/sprinkler	2,153	3,550	39.4
	Gravity	2,474	3,600	39.9
	No irrigation	1,017	1,868	20.7
	Subtotal	5,644	9,018	100.0
All regions	Pressure/sprinkler	12,871	24,259	8.1
	Gravity	9,119	15,737	5.3
	No irrigation	156,577	258,482	86.6
	Totals	178,567	298,478	100.0

It was, therefore, necessary to obtain the raw data from farmer surveys conducted over several years, pool the data, and then aggregate the data according to the state, crop, and time of application. Most of the estimates were derived from the 1990–95 Cropping Practices Surveys (USDA ERS 2000). The Cropping Practices Survey was conducted by the National Agricultural Statistics Service (NASS) in the early 1990s to estimate total commercial fertilizer use on farms. The Cropping Practices Survey has since been integrated into the Agricultural Resource Management Study (ARMS) survey (USDA ERS 2001). A few additional samples were obtained from the 1991 to 1993 Area Studies Survey, a special study conducted by ERS and NASS in selected river basins (Caswell et al. 2001). Farmer survey results were available for 9 of the 15 crops included in this study: corn for grain, soybeans, winter wheat, spring wheat, cotton, sorghum, peanuts, and rice. A total of 75,465 separate farmer survey results were available. These surveys recorded the time of application as: fall application, spring application, application at plant, and application after plant. Since only a few farmers reported nitrogen applications during 3 or more of the time periods, and few farmers reported more than one time of application for phosphorus, the following 11 nitrogen application timing category possibilities were established for each crop, state, and irrigation category:

- Fall nitrogen application only
- Spring nitrogen application only
- At plant nitrogen application only
- After plant nitrogen application only
- Fall and spring nitrogen applications
- Fall and at plant nitrogen applications
- Fall and after plant nitrogen applications
- Spring and at plant nitrogen applications
- Spring and after plant nitrogen applications
- At plant and after plant nitrogen applications
- No nitrogen applications

All records with three or more combinations of nitrogen application times were discarded. In addition, the survey records whether or not manure was applied to the field (although not how much manure was applied). Since manure applications by crop were determined from another source (see next section), it was necessary that these estimates of commercial fertilizer represent the amount of nutrients applied without nutrient supplements from manure. Therefore, all survey records with manure applied were also discarded (about 5% of the available observations).

The application rate was then estimated for each application timing category. First, all multiple applications within a timing category were totaled to provide a total application rate for each timing category. Second, it was necessary to treat nitrogen application rates differently from phosphorus application rates. In many cases, nitrogen was applied but phosphorus was not. In other cases, only phosphorus was applied, usually at low rates. Nitrogen application rates were much more variable than phosphorus application rates. To account for this variability, three separate nitrogen application rate categories were established for each timing category on the basis of the total amount of nitrogen applied to the field for the year. The high application rate category was the highest third of the samples within each timing category, the low application rate category was the lowest third of the sample, and the medium category was the remaining third. Each of these three categories was then split into two categories to account for phosphorus use: cases with no phosphorus applications, and cases with phosphorus applications. An additional application rate category represented survey samples where no nitrogen was applied but phosphorus was applied. This scheme resulted in the following seven nutrient application rate categories:

- High N and average non-zero P
- High N and zero P
- Medium N and average non-zero P
- Medium N and zero P
- Low N and average non-zero P
- Low N and zero P
- Zero N and average non-zero P

After all the survey samples were assigned to a nitrogen timing category and to a nutrient application rate category, the average nitrogen application rate was estimated for the group. Where there was more than one time of nitrogen application (such as fall and spring applications), separate nitrogen application rates were

calculated for each time of application. Where phosphorus was applied in more than one time period, the average rate of application was estimated using all the samples available and the time of phosphorus application was determined as the time period with the highest frequency of occurrence among the samples in the nutrient application rate category.

In all, there were 62 nutrient application possibilities defined for each crop, state, and irrigation category. Only the dominant combinations of timing and rate were chosen to represent commercial fertilizer applications for the model simulations. In many cases, it was necessary to combine states to get an adequate sample size to estimate application rates. Nutrient application possibilities with low sample sizes were discarded. For most crops and states, this resulted in one to four application timing categories, each with about three to six application rate categories. Table 15 provides a specific example of the nitrogen and phosphorus application rates used in the EPIC simulations for Nebraska corn. In most cases, the selected possibilities represented 70 percent or more of the observations for a given crop and state. Overall, 60,004 observations were used to estimate commercial fertilizer application rates, representing about 87 percent of the survey samples available for non-irrigated crops and about 74 percent of the survey samples available for irrigated crops. The number of farmer survey samples used to estimate application rates are shown by crop and state (or state combination) in table 16.

Phosphorus application rates in the farmer survey database (and in table 15) are as pounds of phosphate fertilizer equivalent (P_2O_5). The EPIC model requires that they be converted to pounds of elemental phosphorus (P). Thus, all commercial phosphorus application rates were multiplied by 0.44 (0.44 pounds of elemental phosphorus in one pound of P_2O_5).

The survey results were also used to estimate the probability that a specific nutrient application scenario would occur. These probabilities were estimated as the frequency of occurrence of each of the specific scenarios on the basis of the sample size. An example calculation is shown in table 15. In addition, the percentage of the observations that applied nitrogen by knifing it in or injection was recorded for each combination of categories.

Farmer survey data were not available for grass hay, alfalfa hay, mixed hay, barley, oats, or corn for silage. For alfalfa hay and grass hay, it was assumed that 40 percent of the acres would not receive commercial fertilizer applications. For the remaining 60 percent of the acres, alfalfa received 60 pounds per acre of nitrogen and 26.4 pounds P_2O_5 applied at plant, and grass hay received 110 pounds of nitrogen per acre and 17.6 pounds of P_2O_5 applied at plant. Separate model runs were made for the hayland that received commercial fertilizers and hayland that did not. For corn for silage, nutrient application scenarios for corn for grain were used. For barley and oats, nutrient application scenarios for spring wheat were used. A comparison was done between farmer survey results for oats and barley versus spring wheat for a small number of observations reported by NASS for years prior to 1990. Based on this comparison, the nutrient application rates for spring wheat in Minnesota closely approximated those for barley in major producing states, and nutrient application rates for spring wheat in Montana closely approximated those for oats in major producing states. Consequently, nutrient applications for Minnesota spring wheat were used for barley in Idaho, Minnesota, Montana, North Dakota, South Dakota, and Washington. Nutrient applications for Montana spring wheat were used for oats in Iowa, Minnesota, Montana, North Dakota, South Dakota, Texas, and Wisconsin.

There were several states and crops with acreage in the NRI that were not included in the farmer survey database. In some cases, nutrient application rates from other states were used for these crops; this imputation applied to 11.6 million acres (table 17). For other crops, commercial fertilizer applications were derived to emulate nitrogen applied at nitrogen-standard rates with phosphorus applications at levels that would typically be found in animal manures applied at these rates. The application time was at plant. A total of 5.8 million acres were handled in this manner.

For modeling the selected nutrient application possibilities with EPIC, fall applications were set at 30 days after the harvest of the previous crop, spring applications were set at 30 days before planting, and after plant applications were set at 30 days after planting. (Planting and harvest dates were set using the HUSC, but the timing relative to planting and harvest remained fixed.)

Table 15 Example of nutrient application rates used in EPIC model simulations for corn in NE, derived from Cropping Practice Survey data

Nutrient application scenario	Application rate (lb/a) 1st N application	2nd N application	P application (as P_2O_5)	Time of application for phosphorus	Average yield (bu/a)	Number of survey samples	Aggregation weight (probability of occurrence)
NON-IRRIGATED CORN							
FALL ONLY:							
High N rate and avg. non-zero P rate	139	NA	48	Fall	124.5	8	0.015
High N rate and zero P rate	126	NA	NA	NA	114.3	33	0.063
Medium N rate and avg. non-zero P rate	99	NA	43	Fall	111.2	8	0.015
Medium N rate and zero P rate	100	NA	NA	NA	103.6	37	0.071
Low N rate and avg. non-zero P rate	58	NA	34	Fall	67.4	19	0.036
Low N rate and zero P rate	56	NA	NA	NA	63.7	23	0.044
SPRING ONLY:							
High N rate and avg. non-zero P rate	144	NA	34	Spring	134.8	28	0.054
High N rate and zero P rate	141	NA	NA	NA	104.6	39	0.075
Medium N rate and avg. non-zero P rate	99	NA	41	Spring	104.3	32	0.061
Medium N rate and zero P rate	98	NA	NA	NA	108.4	37	0.071
Low N rate and avg. non-zero P rate	58	NA	41	Spring	85.6	24	0.046
Low N rate and zero P rate	67	NA	NA	NA	93.2	44	0.084
SPRING-AT PLANT:							
High N rate and avg. non-zero P rate	113	21	42	At plant	93.3	31	0.059
Medium N rate and avg. non-zero P rate	85	14	26	At plant	98.4	32	0.061
Low N rate and avg. non-zero P rate	51	10	32	At plant	83.1	30	0.057
AT/AFTER PLANT:							
High N rate and avg. non-zero P rate	20	120	36	At plant	100.0	24	0.046
Medium N rate and avg. non-zero P rate	14	80	29	At plant	63.5	27	0.052
Low N rate and avg. non-zero P rate	13	42	35	At plant	93.8	26	0.050
NO COMMERCIAL FERT. APPLIED	0	0	0	NA		21	0.040
Weighted average for non-irrigated corn	79.9	14.4	19.6		Sum =	523	1.000

Table 15 Example of nutrient application rates used in EPIC model simulations for corn in NE, derived from Cropping Practice Survey data—Continued

	Application rate (lb/a)						
Nutrient application scenario	**1st N application**	**2nd N application**	**P application (as P_2O_5)**	**Time of application for phosphorus**	**Average yield (bu/a)**	**Number of survey samples**	**Aggregation weight (probability of occurrence)**
IRRIGATED CORN							
FALL ONLY:							
High N rate and avg. non-zero P rate	197	NA	35	Fall	167.3	21	0.017
High N rate and zero P rate	198	NA	NA	NA	168.8	15	0.012
Medium N rate and avg. non-zero P rate	177	NA	67	Fall	137.0	12	0.010
Medium N rate and zero P rate	173	NA	NA	NA	150.3	32	0.026
Low N rate and avg. non-zero P rate	126	NA	27	Fall	139.0	16	0.013
Low N rate and zero P rate	129	NA	NA	NA	121.4	23	0.019
SPRING ONLY:							
High N rate and avg. non-zero P rate	197	NA	43	Spring	168.6	45	0.037
High N rate and zero P rate	197	NA	NA	NA	163.1	52	0.043
Medium N rate and avg. non-zero rate	163	NA	39	Spring	167.5	46	0.038
Medium N rate and zero P rate	161	NA	NA	NA	134.2	48	0.040
Low N rate and avg. non-zero P rate	111	NA	33	Spring	140.9	30	0.025
Low N rate and zero P rate	118	NA	NA	NA	148.8	56	0.046
FALL-AT PLANT:							
High N rate and avg. non-zero P rate	194	12	39	At plant	151.9	46	0.038
Medium N rate and avg. non-zero P rate	164	10	25	At plant	155.7	52	0.043
Low N rate and avg. non-zero P rate	122	9	25	At plant	140.3	45	0.037
SPRING-AT PLANT:							
High N rate and avg. non-zero P rate	188	15	34	At plant	161.7	105	0.086
Medium N rate and avg. non-zero P rate	149	18	31	At plant	147.3	105	0.086
Low N rate and avg. non-zero P rate	102	13	29	At plant	157.3	106	0.087
AT/AFTER PLANT:							
High N rate and avg. non-zero P rate	29	173	38	At plant	145.9	121	0.100
Medium N rate and avg. non-zero P rate	24	131	33	At plant	143.9	123	0.101
Low N rate and avg. non-zero P rate	21	73	31	At plant	131.0	116	0.095
Weighted average	116.8	42.7	27.2		Sum =	1,215	1.000

NA=not applicable.
Note: There were a total of 2,457 survey observations for corn in Nebraska: 1,681 were irrigated and 776 were non-irrigated. Of the 62 nutrient application possibilities for non-irrigated corn, 51 were represented in the survey observations; the dominant nutrient application possibilities were the 19 presented in the table, representing 523 of the original 776 survey observations (67%). Of the 62 possibilities for irrigated corn, 57 were represented in the survey observations; the dominant nutrient application possibilities were the 21 presented in the table, representing 1,215 of the original 1,681 survey observations (72%).

Table 16 Number of farmer survey samples used to estimate nutrient application rates used in EPIC model simulations

Crop	States or state combinations	Non-irrigated crops		Irrigated crops	
		Number of survey samples used	Percent of total survey samples	Number of survey samples used	Percent of total survey samples
Corn	IN	1,520	74	—	—
	AL, GA, FL, MS, AR, LA	492	87	27	21
	CO, KS	217	70	233	68
	MD, DE, VA, WV	161	76	—	—
	TX, NM, OK, AZ	321	72	173	72
	MT, ND, WY, SD	985	84	17	24
	NE	523	67	1,215	72
	MO	881	77	73	43
	CA, NV, UT, ID, OR, WA	—	—	90	75
	ME, CT, PA ,NY, NJ, MA, NH, RI, VT	316	72	—	—
	NC, SC	669	75	—	—
	KY, TN	632	74	—	—
	MI	772	76	79	75
	WI	673	74	—	—
	MN	1,418	79	—	—
	IA	2,364	79	—	—
	OH	1,151	69	—	—
	IL	2,204	75	—	—
Soybeans	AL, FL, GA	633	95	—	—
	AR	823	97	553	95
	DE, MD, PA, NJ, VA	293	81	—	—
	KY	671	96	—	—
	KS	539	95	17	43
	LA	634	98	—	—
	MN	1,504	98	42	78
	MI, WI	123	79	—	—
	ND, SD	533	95	—	—
	NC, SC	735	94	—	—
	MS	722	98	84	90
	MO	1,268	98	92	76
	NE	753	95	167	81
	OH	1,406	99	—	—
	TN	675	98	—	—
	TX, OK	46	82	—	—
	IN	1,526	99	—	—
	IL	2,089	99	—	—
	IA	2,001	99	—	—

Table 16 Number of farmer survey samples used to estimate nutrient application rates used in EPIC model simulations—Continued

		Non-irrigated crops		Irrigated crops	
Crop	**States or state combinations**	**Number of survey samples used**	**Percent of total survey samples**	**Number of survey samples used**	**Percent of total survey samples**
Winter wheat	WA	639	92	28	38
	TX	605	87	212	84
	SD	305	88	—	—
	OR	332	85	12	29
	OH	339	87	—	—
	OK	1,084	91	—	—
	NE	449	89	—	—
	MT	468	90	—	—
	MO	353	92	—	—
	KS	1,547	97	43	49
	IL, IN	443	85	—	—
	ID	213	77	123	79
	CO	366	90	24	63
	AR	175	89	—	—
	AL, GA, FL, NC, VA*	407	100	78	100
Spring wheat	ND	1,272	96	—	—
	MN	397	89	—	—
	MT	341	84	—	—
	SD	289	91	—	—
Cotton	CA	—	—	892	94
	AR	232	77	324	79
	AZ	—	—	352	85
	LA	267	87	130	72
	MS	642	89	150	66
	TX	1,565	93	1,038	91
	AL, GA, FL, NC, VA*	306	100	80	100
Sorghum	KS, NE, TX	544	77	42	46
Rice	LA	—	—	430	86
	AR	—	—	606	84
Peanuts	GA	192	97	52	93
	TX	104	90	89	82
	NC, VA	150	95	—	—
Potatoes	CO	—	—	271	80
	ID	—	—	1,159	73
	MN	394	84	93	80
	MI	85	61	226	69
	ME	779	96	66	70

Table 16 Number of farmer survey samples used to estimate nutrient application rates used in EPIC model simulations—Continued

Crop	States or state combinations	Non-irrigated crops		Irrigated crops	
		Number of survey samples used	Percent of total survey samples	Number of survey samples used	Percent of total survey samples
Potatoes	ND	330	78	130	63
	NY	214	87	213	90
	PA	246	84	49	77
	WI	33	52	594	93
	WA	24	62	733	83
	OR	—	—	499	68
All crops	**All states**	49,440	87	10,564	74

Note: Dashes denote that sufficient data were not available to estimate nutrient application rates.
* Derived from area studies survey data.

Table 17 Cases where nutrient application rates were imputed from other states or were based on nitrogen-standard application rates

Crop	States where nutrient application scenarios from other states were used	Acres (1,000s)	States where nutrient application scenarios were based on nitrogen-standard application rates	Acres (1,000s)
Corn for grain, non-irrigated	None	0	None	0
Corn for grain, irrigated	None	0	None	0
Soybeans, non-irrigated	None	0	CO, NY, WV	120
Soybeans, irrigated	SD, ND	138	CO	16
Sorghum, non-irrigated	AR, MO, OK, SD	741	AL, CO, DE, FL, GA, ID, IL, IN, IA, KY, LA, MD, MS, NJ, NM, NC, ND, OH, PA, SC, TN, VA, WI	749
Sorghum, irrigated	AR, MO, OK, SD	117	AZ, CA, CO, GA, IN, LA, MS	60
Cotton, non-irrigated	KS, MO, NM, OK, SC, TN	1,335	None	0
Cotton, irrigated	KS, MO, NM, OK, SC, TN	0	None	326
Peanuts, non-irrigated	AL, FL, OK	456	AR, MS, SC	15
Peanuts, irrigated	AL, FL, OK	118	AR, LA, NM, SC	29
Winter wheat, non-irrigated	KY, MI, MS, NM, TN, WY	1,684	CA, DE, LA, MD, MN, ND, NJ, NY, SC, UT, WV, WI	1,568
Winter wheat, irrigated	NM	135	AZ, CA, DE, IA, MD, NV, NJ, SC, UT	465
Spring wheat, non-irrigated	WY	21	CO, ID, NJ, OR, WA	202
Spring wheat, irrigated	None	0	AZ, CA, NV, OR, UT	200
Rice	MS, MO, TX	759	CA, MN	617
Potatoes, non-irrigated	None	0	AL, FL, GA, LA, MA, MS, MO, NJ, OH, TN, VT	63
Potatoes, irrigated	None	0	CA, DE, FL, IN, KS, LA, MO, NJ, NM, NC, TX, VA	101
Barley, non-irrigated	ID, MN, MT, ND, SD, TX, WI	3,436	CA, CO, GA, IA, KY, MD, ME, MI, MS, NC, NE, NJ, NY, OH, OR, PA, UT, VA, WY	295
Barley, irrigated	None	0	AZ, CA, CO, MD, MO, OR, UT, VA, WY	222
Oats, non-irrigated	IA, MN, MT, ND, SD, TX, WI	2,913	AR, CA, CO, FL, IL, IN, KS, LA, MD, ME, MI, MS, NC, NE, NY, OH, OK, OR, PA, SC, TN, VA, WY	683
Oats, irrigated	None	0	CA, CO, ID, KS, MI, NC, NE, NJ, NM, UT, WA, WY	97
Total acres (1000s)		11,583		5,827

EPIC requires information on the form of nitrogen applied—either applied as elemental nitrogen or as anhydrous ammonia. If the method of application was injection or knifed in, it was assumed that the form of nitrogen was anhydrous ammonia. If not, nitrogen was applied as elemental nitrogen using a broadcast method of application. Where a portion of the nitrogen applied was injected, two nitrogen applications were simulated in the EPIC model run—one for the injected portion and another for the amount broadcast applied. In EPIC, anhydrous ammonia was applied at the 150-millimeter depth while the elemental nitrogen was applied to the surface.

Representing manure applications in the model

Only an incidental amount of information on manure applications is available from farmer surveys, which was inadequate for representing manure applications for this study. Manure applications were derived from estimates of manure application rates created in a recent study on the costs of implementing Comprehensive Nutrient Management Plans (CNMP) (USDA NRCS 2003). In that study, a baseline scenario was constructed using information from the 1997 Census of Agriculture (USDA NASS 1999) that simulated manure applications for 1997, emulating pre-CNMP land application practices. County estimates were made of the total amount of manure nutrients available for land application, which were converted to crop-specific estimates of manure application rates and percentage of acres receiving manure. In estimating crop-specific application rates, manure was allocated to crops using a priority approach. The highest priority crops were allocated the manure first. The highest priority crops were corn, sorghum, silage crops, and hayland (USDA NRCS 2003, app. B.)

Separate estimates were made for land application on livestock operations (manure producing farms) and land application on surrounding properties (manure receiving farms). In deriving these manure applications, the following assumptions were made:

- manure receiving farms would apply manure at nitrogen-standard rates for all crops
- manure producing farms would apply manure at nitrogen-standard rates for alfalfa hay, soybeans, potatoes, cotton, and all close grown crops
- manure producing farms would apply manure at rates above the nitrogen-standard rates (determined in part by the amount of land available on the farm) for corn, sorghum, other hay land, and pastureland.

Because different application rates were available for manure producing farms and manure receiving farms, separate EPIC model runs were created for each of these two cases.

For this study, these county estimates were converted to estimates of application rates and percentage of acres treated for each crop in each state and climate cluster combination. To avoid distortions in the model results that would arise because of differences in crop yields between the EPIC model results and the crop yields from the Census of Agriculture, which were the basis for calculating application rates related to the nitrogen standard, application rates were adjusted to correspond to the yields produced using EPIC. This adjustment was based on the relationship between yield and application rate in the estimates derived from the Census of Agriculture. For each state, crop, and climate zone, five yield classes were created on the basis of yields obtained from EPIC model runs using only commercial fertilizer applications. Yield classes were constructed so as to roughly represent equal acreage. (In cases where there was little variability in EPIC yields, fewer yield classes were created.) For each yield class, a manure application rate was calculated using the yield-application rate relationship determined from the results of the previous study by NRCS. An additional adjustment was also made to the estimates of the percentage of acres with manure applied to make sure that the yield-based adjustment did not lead to the application of more or less manure in a region than was produced by livestock operations in that region.

An example of manure application rates used in the EPIC model simulations is shown in table 18 for Nebraska corn, where there are three climate clusters. The table shows how manure nitrogen (N) and manure phosphorus (P) application rates increase as yields increase. The application rates shown only apply to URUs in the corresponding yield class. The aggregation weights shown in table 18 are the proportion of acres receiving manure, and were used as estimates of the probability that the manure application option would occur in calculating EPIC model outputs for

Table 18 Example of manure application rates (irrigated and non-irrigated) and supplemental commercial fertilizer application rates for NE corn

			Manure producing farms			Manure receiving farms				Supplemental commercial fertilizer application rates (lb/a)**			
			Application rate (lb/a)*			Application rate (lb/a)*				Manure producing farms		Manure receiving farms	
Climate cluster	Yield class (bu/a)	NRI acres in yield class	N	P	Climate cluster aggregation weight	N	P	Climate cluster aggregation weight	Yield class index	N	P	N	P
1	66.3–77.0	1,400,938	146	64	0.019	79	37	0.034	0.549	1.5	0.0	15.3	0.0
1	77.0–145.5	1,283,418	226	99	0.019	122	58	0.034	0.851	2.3	0.0	23.8	0.0
1	145.5–153.4	1,414,904	304	134	0.019	164	78	0.034	1.144	3.1	0.0	32.1	0.0
1	153.4–157.2	1,273,095	316	139	0.019	170	81	0.034	1.189	3.3	0.0	33.8	0.0
1	157.2–178.6	1,317,104	342	150	0.019	184	88	0.034	1.287	3.5	0.0	36.5	0.0
	Total	6,689,459											
3	89.1–121.0	350,360	211	86	0.017	117	56	0.024	0.741	0.0	0.0	12.7	0.0
3	121.0–128.5	336,107	251	102	0.017	138	66	0.024	0.882	0.0	0.0	16.0	0.0
3	128.5–151.8	334,398	282	115	0.017	156	74	0.024	0.990	0.0	0.0	17.3	0.0
3	151.8–164.5	420,566	318	129	0.017	176	84	0.024	1.117	0.0	0.0	19.5	0.0
3	164.5–214.6	249,803	381	155	0.017	210	100	0.024	1.338	0.0	0.0	24.0	0.0
	Total	1,691,234											
27	64.8–142.4	53,551	218	106	0.028	119	60	0.080	0.721	0.0	0.0	8.5	0.0
27	142.4–152.6	76,628	311	151	0.028	170	85	0.080	1.029	0.0	0.0	12.0	0.0
27	152.6–154.6	32,459	324	157	0.028	177	88	0.080	1.072	0.0	0.0	12.6	0.0
27	154.6–158.9	53,453	330	160	0.028	181	90	0.080	1.092	0.0	0.0	12.3	0.0
27	158.9–164.1	43,987	340	165	0.028	186	93	0.080	1.125	0.0	0.0	13.0	0.0
	Total	260,078											

* Application rates are pounds of elemental N or elemental P.

** For nitrogen, the expected commercial fertilizer application rate is 135.6 pounds per acre if manure were not going to be applied (state average rate). For phosphorus, it is 10.7 pounds per acre as elemental P.

NRI cropland sample points. In cluster 1, for example, 1.9 percent of the corn acres received manure at rates associated with manure producing farms and 3.4 percent received manure at rates associated with manure receiving farms. In total, 5.3 percent of the corn acres in cluster 1 received manure in the EPIC model simulations. In cluster 3, a total of 4.1 percent of the corn acres received manure, and in cluster 27, a total of 10.8 percent of the corn acres received manure.

Commercial fertilizers are also applied on fields receiving manure in the model simulations, but at lower rates than on fields without manure applications. Since there was not enough data from farmer surveys to estimate commercial fertilizer application rates on fields receiving manure, the approach taken in this study was to estimate the amount of commercial fertilizer that might have been applied had manure not also been applied, and then reduce those commercial fertilizer rates by calculating a nutrient credit for the manure applied.

The first step was to estimate the amount of commercial fertilizer expected to be applied if no manure was applied. For this, the average annual nitrogen and phosphorus application rate was calculated for each state and crop from the farmer survey data used to estimate commercial fertilizer applications. For example, the following estimates were obtained for corn in Nebraska, derived as weighted averages from the commercial fertilizer rates shown in table 15.

	Annual N application rate (lb/a)	Annual P application rate (lb/a)	
		P as P_2O_5	Elemental P
Non-irrigated corn, NE	94.2	19.6	8.6
Irrigated corn, NE	159.5	27.3	12.0
Acreage-weighted average for state	135.6	24.4	10.7

NRI acreage for irrigated and non-irrigated crops was used to derive an acreage-weighted average application rate to represent the expected commercial fertilizer application if no manure was applied. Thus, for the Nebraska example, the state average nitrogen rate was 135.6 pounds per acre and the state average phosphorus rate was 10.7 pounds per acre (as elemental P). (According to the NRI, there were 3.239 million acres of non-irrigated corn and 5.599 million acres of irrigated corn in Nebraska in 1997.)

The second step was to convert the state average rate to an expected rate for each of the yield classes. This was done by constructing a yield index such that the acreage-weighted average yield would have an index value of 1. Multiplying this index times the state average application rate produced estimates for each yield class of the commercial fertilizer application rate that would generally be expected if no manure were to be applied.

The last step was to adjust these rates downward by applying a nutrient credit for the manure that was applied. It was assumed that manure producing farms would take a manure nutrient credit of 50 percent of the amount of manure nutrients applied. Thus, if the manure nitrogen application rate was 150 pounds per acre and the manure phosphorus application rate was 60 pounds per acre, the nitrogen credit would be 75 pounds per acre, and the phosphorus credit would be 30 pounds per acre. If the commercial fertilizer application possibility was 100 pounds per acre for commercial nitrogen fertilizer, the commercial fertilizer application rate would be reduced to 25 pounds per acre for model runs where manure was also applied. In some cases, this nutrient credit adjustment resulted in no commercial fertilizer applications. In the hypothetical example presented above, commercial nitrogen application rates less than 75 pounds per acre would be adjusted to zero. Because manure receiving farms are mostly crop producers, and therefore, do not need to address a manure disposal situation, a higher manure nutrient credit was used for manure receiving farms—75 percent of the amount of manure nutrients applied.

A specific example of how nitrogen and phosphorus credits affected supplemental commercial fertilizer application rates for cases where manure is applied is presented in table 18 for corn in Nebraska. The expected commercial fertilizer application rate for nitrogen is 135.6 pounds per acre if manure were not going to be applied. In the case of the lowest yield class in climate cluster 1, for example, the expected nitrogen application rate was 75 pounds per acre (135.6 times the yield index of 0.549), and the expected phosphorus rate was 5.9 pounds per acre as elemental P. Thus, the nitrogen credit was 73.5 pounds per acre for manure producing farms and 59.7 pounds per acre for manure receiving farms in this yield class, which resulted in estimates of supplemental commercial fertilizer applications of 1.5 and 15.3 pounds per acre for manure producing farms and manure receiving farms, respectively. For phos-

phorus, the credit was 32 pounds per acre for manure producing farms and 28 pounds per acre for manure receiving farms, but because the expected application rate was lower than the credit estimate, no supplemental phosphorus was applied in the model simulation in this case. Supplemental commercial fertilizer application rates for the other yield classes and climate clusters shown in table 18 were calculated similarly.

The manure credit assumptions were applied to all parts of the country. However, there is evidence that manure credits are not always taken into account by crop producers, especially on farms with livestock operations. For example, Gallepp (2001) and Shepherd (2000) report that beef and dairy farmers over applied nitrogen and phosphorus on average by 38 and 74 pounds per acre, respectively in Wisconsin, based on a survey of about 1,900 livestock producers. The results were skewed by extreme applications applied by about 20 percent of the producers; nevertheless, few producers were found to be crediting nutrients appropriately. Gassman et al. (2002) also report that a survey of livestock producers in the Upper Maquoketa River watershed in eastern Iowa showed that little or no crediting of manure nutrients was common in that area. Gassman et al. (2003) also report only modest manure nutrient crediting among livestock producers in the Mineral Creek Watershed, also located in eastern Iowa.

For EPIC model simulations, it is also necessary to establish application methods and times of application for manure applications. For the manure producing farm case, manure was surface applied without incorporation at three application times:

- 50 percent of the manure was applied in the fall 15 days after the harvest of the last crop
- 15 percent of the manure was applied on February 1
- 35 percent of the manure was applied in the spring 20 days before planting

For the manure receiving farm case, manure was surface applied 2 days before the primary tillage except for no-till simulations, where half of the manure was injected and half was surface applied 20 days before planting. For winter wheat, manure was applied 15 days before fall planting in both cases. For hayland in both cases, 15 percent of the manure was applied on February 1 and the remainder was applied at intervals following each cutting. All supplemental commercial fertilizer applications were applied at plant. (Planting and harvest dates were set using the heat unit scheduling code, but the timing relative to planting and harvest remained fixed.)

The 1997 Census of Agriculture database was also used to derive the proportion of manure nitrogen that was in mineral form, organic form, or available as ammonia, which is needed to run the EPIC model. These estimates were based largely on the livestock type and assumptions about manure handling technologies. The proportion of manure phosphorus in mineral form and organic form was also derived. These proportions were determined for each state-climate zone combination for use in making EPIC model runs.

Only about 4 percent of the acres had manure applications in the EPIC model simulations (table 19), representing about 11 million acres. The majority of manure applications were for corn silage, corn, and grass hay.

Maps of per-acre estimates of model output

The spatial distribution of per-acre model output is shown in maps created using a GIS-based approach developed specifically for mapping NRI variables. The mapping procedure is a grid-based approach that takes advantage of the coordinate locations of NRI sample points and involves calculation of weighted averages by grid cell areas and the application of interpolation and smoothing techniques. The purpose of the mapping technique is to illustrate spatial trends and patterns in the model results.

Prior to mapping, the database was censored slightly to reduce the number of isolated sample points. This was done primarily to ensure that the locations of the NRI sample points were not revealed in the map product, as the NRI sample frame is proprietary and protected by federal confidentiality rules and regulations. In areas where points are relatively close together, the data aggregation, interpolation, and smoothing procedures effectively conceal the precise location of individual sample points. NRI sample points were censored such that at least two primary sampling units (PSU), and a total of four cropland sample points were contained in each 20 by 20-kilometer (400 km^2) grid

cell (12.4 by 12.4 mi, 154 mi^2). NRI cropland sample points not meeting these criteria were considered isolated points and were not included in the mapping analysis. A total of 6,196 NRI sample points were excluded from the results shown in the maps as a result of this censoring procedure, representing about 2.8 percent of the sample points in the NNLSC database and approximately 3.9 percent of the acres. Censoring applied only to the results shown in the maps; summary statistics presented in tables in this report include the full set of NRI sample points in the NNLSC database.

The mapping procedure is basically a three step process:

Step 1. Calculate grid cell values for cells that contain data.

Step 2. Interpolate (predict) values for cells that have no data.

Step 3. Perform a geographic transformation when representing the grid cells for display on a map.

Mapping was performed using ESRI's ArcGIS software version 9.0.

The first step is to calculate the weighted average (using the NRI expansion factor as the weight) of all data values associated with points found within each 25-

Table 19 Representation of manured acres in the model simulations

	No manure		Manure producing farms		Manure receiving farms		Total manured acres	
Crop	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**
Barley	4,567,608	98.6	11,946	0.3	55,347	1.2	67,293	1.5
Corn	72,874,682	93.2	2,001,884	2.6	3,342,774	4.3	5,344,658	6.8
Corn silage	3,547,540	68.3	1,564,899	30.1	84,220	1.6	1,649,119	31.7
Cotton	16,169,723	95.9	32,285	0.2	656,191	3.9	688,476	4.1
Grass hay	13,500,009	92.5	677,288	4.6	419,003	2.9	1,096,291	7.5
Legume hay	24,710,636	99.7	39,612	0.2	25,352	0.1	64,964	0.3
Oats	3,745,858	99.3	2,988	0.1	23,554	0.6	26,542	0.7
Peanuts	1,820,542	98.8	4,374	0.2	18,484	1.0	22,858	1.2
Potatoes	966,180	97.9	473	0.1	20,047	2.0	20,520	2.1
Rice	3,636,996	100.0	146	<0.1	157	0.0	303	<0.1
Spring wheat	20,392,934	99.5	4,492	<0.1	105,713	0.5	110,205	0.5
Sorghum	10,511,384	96.5	31,177	0.3	354,738	3.3	385,915	3.5
Soybeans	67,131,262	99.4	99,092	0.2	312,446	0.5	411,538	0.6
Winter wheat	44,041,606	97.8	73,424	0.2	898,932	2.0	972,356	2.2
All crops	287,616,962	96.4	4,544,080	1.5	6,316,958	2.1	10,861,038	3.6

square-kilometer grid cell area (9.6-mi^2 grid cell area). The grid function sets the center point of each cell that contains one or more NRI points to the weighted average value. While many cells have multiple NRI points within them that get averaged together, many others cells have no NRI points and are referred to as unpopulated cells; the value for unpopulated cells remains null or undefined after this first step.

The next step is to use the mean values associated with the center points of populated cells in an interpolation function to generate values for the unpopulated cells. The goal of interpolating is to populate surrounding empty cells with predicted values in order to provide a smoother, easier-to-interpret look at the geographic distribution of the populated cell values. There are several commonly used types of interpolation models, including Inverse Distance Weighted (IDW), polynomial trend surface, spline, and Kriging. IDW was chosen for its relative simplicity of calculation and because of its suitability for representing surfaces that may at times be sharply varied rather than gently varied. All interpolation functions assume that spatially distributed phenomena are spatially correlated. If no populated cell center points are found within the neighborhood, as would occur in areas with little or no cropland, the cell value remains unpopulated. When a cell is populated by means of interpolation, it is not further used in the calculation of other unpopulated cells still to be interpolated.

Those points nearest to the prediction cell are given greater weight in the calculation of the predicted value than are those further away. This is implemented through what is referred to as an exponent of distance. The value 2 was chosen for the exponent, the default used by ESRI and also known as inverse distance squared interpolation. It causes the influence of surrounding values to decrease rapidly with increasing distance from the predicted cell. Smaller exponents result in smoother, more gradual trends and less detailed surfaces.

A 15-kilometer radius size (9.3 mi) was chosen as the neighborhood for the calculation of each interpolated value. The radius size was somewhat arbitrary, but was based upon experimentation with several different radii, and ultimately was a compromise of several objectives including:

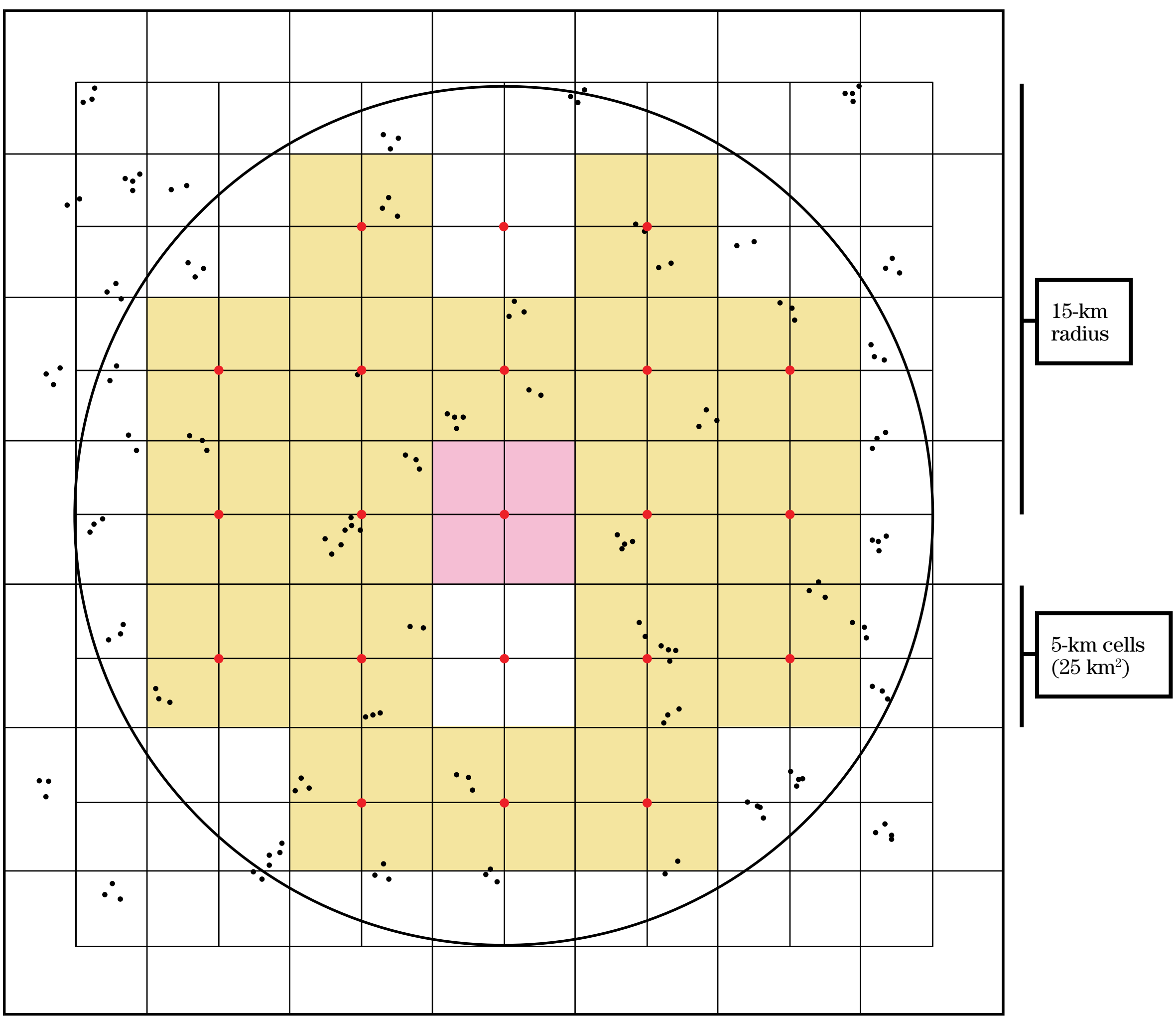
- encompassing the entire area of each 20- by 20-kilometer grid cell used in the censoring process (assuring that every interpolated value results from cropland points in at least two PSUs)
- limiting the area of influence impacting the predicted value of each cell
- limiting the number of surrounding unpopulated cells that would become populated in the course of interpolation
- limiting the cell size to provide a sufficiently high resolution in order to reveal detail in spatial trends across regional areas
- protecting the precise location of NRI sample points

The IDW function also requires input for a maximum number of points to examine, but that maximum was set high enough so that the limiting constraint would be the neighborhood size, effectively assuring that the smallest area mapped would be the size of the neighborhood.

Figure 5 illustrates how the value of each grid cell is determined in the process of interpolation. The black squares represent 5-kilometer length (25-km^2 area) cells of a small grid. The red cell is the prediction cell, the cell for which an interpolated value will be calculated. The lighter background grid simply serves as a measure for showing the center points of cells (shown as red points) that are completely contained within the 15-kilometer radius defined from the center point of the red prediction cell. The black dots represent NRI sample points, with locations that are approximately based upon an actual example. The yellow cells are those completely within the 15-kilometer radius that contain at least one NRI sample point and are therefore populated at the cell center with a weighted average value representing all point values in the cell. Each white cell completely within the radius is unpopulated and has no value until one is predicted for it as the interpolation process proceeds from the upper left cell to the lower right cell across a grid positioned over the United States. If no populated cells are found within the 15-kilometer radius, the prediction cell will remain unpopulated. Potentially, up to 20 cell centers (the red dots in the illustration, excluding the cell being interpolated) within a 15-kilometer radius may be populated with values.

In the final step, a geometric transformation is used to create the values in the output display grid. A resampling method is used to account for the fact that the origin of the output display grid does not line up exactly with the origin of the input point layer or with intermediate grids involved in the calculations. One of three possible resampling techniques can be selected —either nearest neighbor assignment, bilinear interpolation, or cubic convolution resampling. In the case of continuous data, the choice is mainly a matter of aesthetics. Bilinear interpolation resampling was selected for use on these maps because it produced the sharpest output. Bilinear interpolation uses the values of the four nearest cell centers to weight-average a cell value for display on the map.

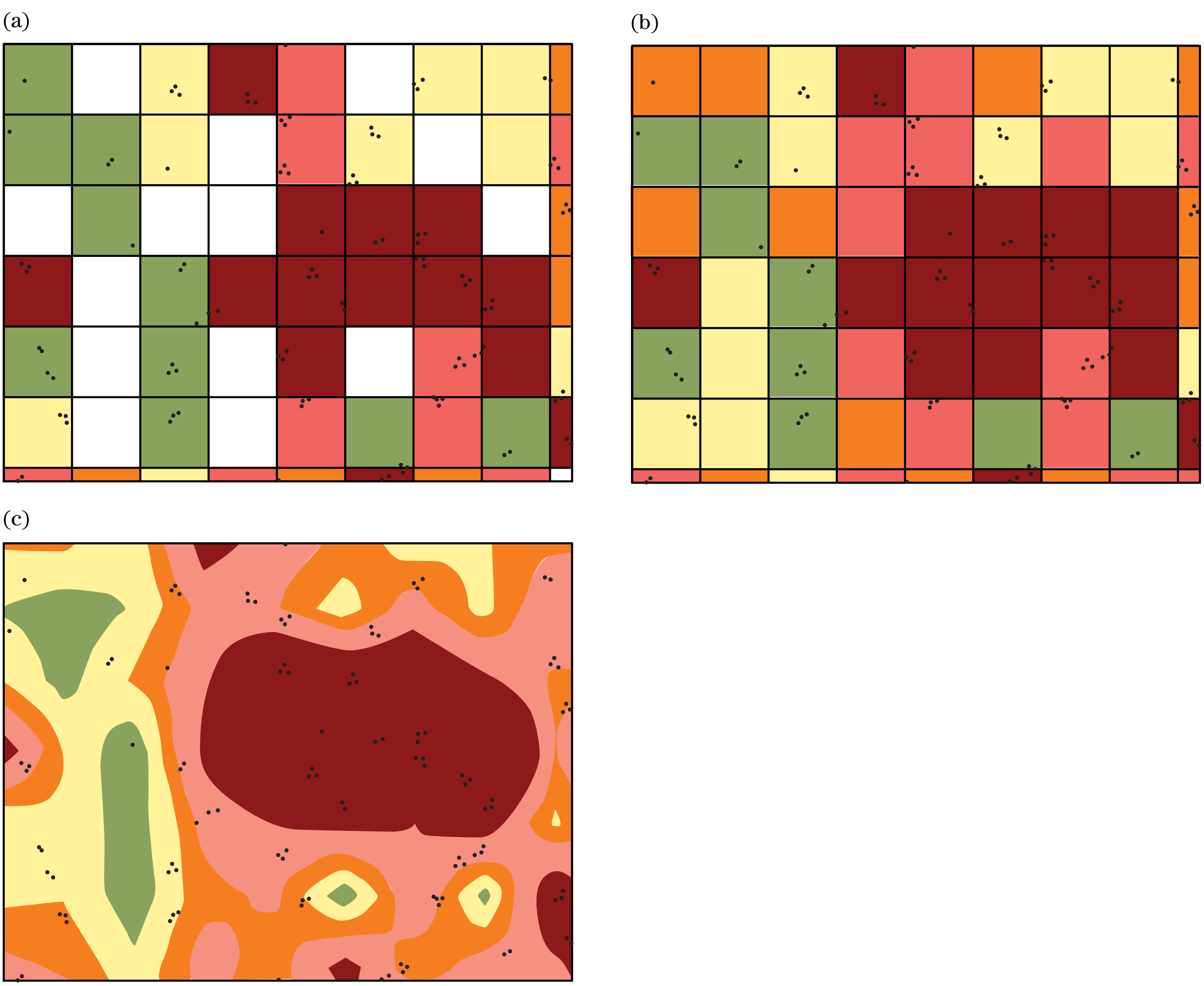
Figure 5 Schematic for illustrating the mapping technique used to display per-acre model output results



The three steps in the mapping process are illustrated in figure 6. Figure 6(a) shows that prior to interpolation, the values for points are weight-averaged and the resulting value is assigned to the cell, while cells lacking points are treated as null values (white cells); (b) shows that after interpolation, null cells within a limited radius of cells containing data are populated with values based upon the interpolation function; and (c) shows how the re-sampling algorithm (in this case, bilinear interpolation re-sampling, which examines 4 surrounding cell values) smoothes the data to represent a more continuous surface. Note that the colors represent classes to which the weight-averaged values are assigned.

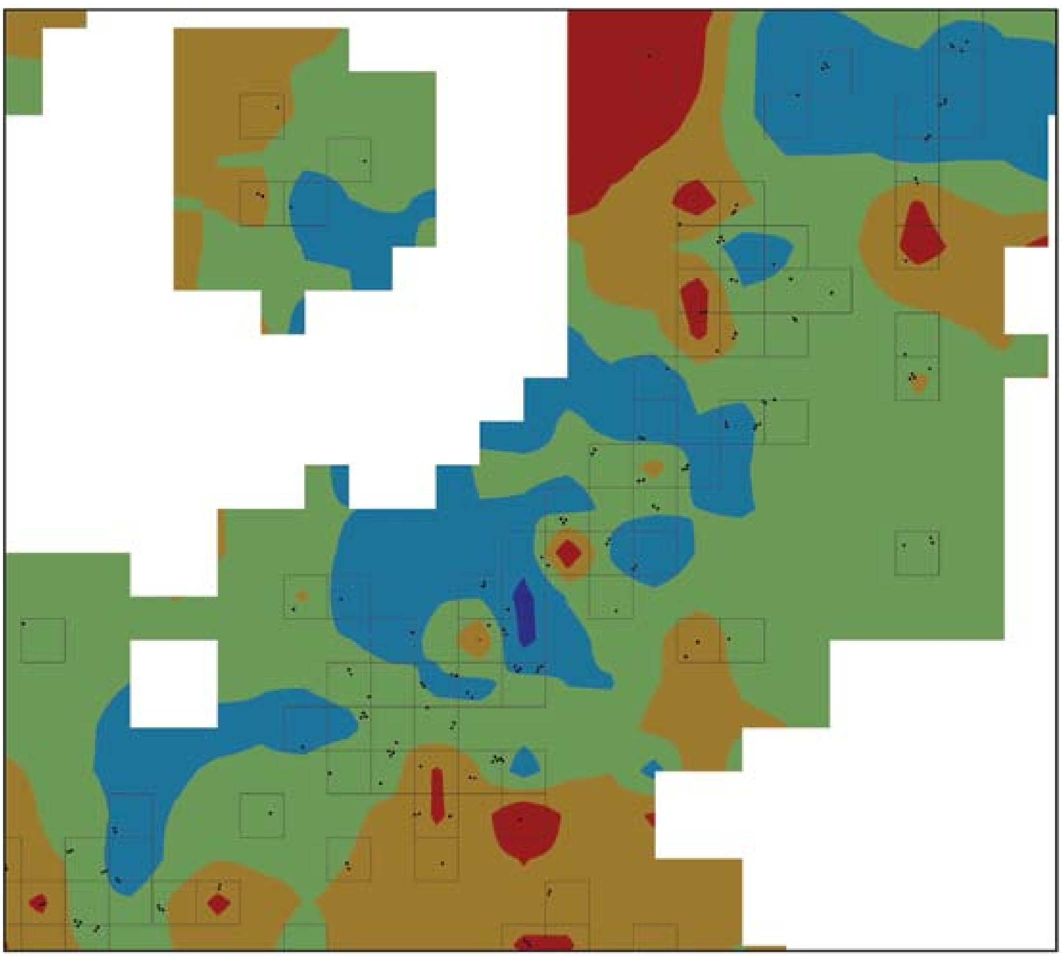
The result provides a geographic representation that is easier to interpret and offers clearer spatial trending than would be revealed by merely examining a map of the point values or by aggregating the data by irregularly shaped polygons. As with polygon-based maps, the numeric range of calculated values is divided into classes, and the classes are color coded to reveal spatial trends. Class breaks and colors were selected to highlight the spatial trends, or in some cases, to allow comparisons among maps of related variables.

Figure 6 Hypothetical example of interpolation and resampling process



The mapping method resulted in a visual representation that greatly overstates the total number of cropland acres. For example, the domain of NRI points used in this study represents a total of 298 million acres, only 287 million of which was used in the mapping after censoring. However, when displayed using the interpolation mapping technique, the spatial representation is equivalent to 925 million acres on the map. The over-representation is most pronounced in areas where land cover is diverse and cropland is not the dominant land use. In large areas where the percentage of the land cover is predominately cropland, the visual over-representation of acres is minimal. Figure 7 is a hypothetical example that demonstrates this over-representation of cropland acres in a setting where land cover is diverse. The EPIC model output estimates presented in the maps only represent the cropland portion of the land cover. Nearly all the colored areas in the maps also include other land covers, such as pastureland, forestland, rangeland, and urban. As shown in figure 7, cropland in some areas is only a small portion of the actual land cover.

Figure 7 Hypothetical example of area over-representation and under-representation



NRI sample points are not evenly distributed, and each sample point may represent anywhere from 100 to 49,500 acres (expansion factors). The median value is 1,500 acres. When NRI sample point expansion factors are summed for each 5-kilometer square grid cell, the total may substantially over-represent or in some cases under-represent the surface area of a 5-kilometer square cell (approximately 6,178 a). The interpolation method fills in additional areas, expanding well beyond the size of the grid cells that contain sample sites and results in a net over-representation of cropland (colored area) acres.

Another source of over-representation of acres occurs because some grid cells contain only a few NRI sample points, representing only a few acres of cropland, while other grid cells represent many more cropland acres. Since all grid cells are the same size, this has the visual effect of exaggerating the cropland representation in some areas of the country relative to other areas of the country. Areas where cropland is a small share of the land use on the landscape appear over-represented in the maps.

The percentage of acres associated with the class breaks used to construct the maps is reported in the map legend to provide a perspective on the extent of the over-representation of acres in the maps. These percentages were calculated on the basis of the individual NRI sample points, and not on the basis of the average values for the map cells. Thus, the percentages reported in the map legend do not account for the averaging effect originating from use of the mean values to represent model output for each map cell.

The NRI sample frame was designed to provide statistically reliable estimates at the national, state, and sometimes sub-state levels. However, it was not designed to provide statistically reliable estimates for the small grids used to construct the maps presented in this report. Therefore, caution must be exercised in interpreting the information depicted on the maps. The purpose of the maps is to show spatial trends; localized interpretations of results are inappropriate and may be misleading.

Maps of total loading estimates

Maps of per-acre model outputs are useful for identifying areas of the country where conservation practices would be expected to have the greatest impact on reducing sediment and nutrient losses from farm fields, wind erosion, and soil quality degradation. In some cases, however, the focus for implementation of conservation practices is on reducing the total loadings of nutrients and sediment within a region. An example would be to address downstream water quality degradation, such as impaired water quality in estuaries or in the oceans. For these concerns, cropland areas exporting the largest amounts of sediment and nutrients would constitute priority areas. Annual loadings estimates in total tons are shown in these maps, representing field-level losses of potential pollutants. These estimates were derived by multiplying the annual average per-acre model output times the number of acres represented by the NRI sample points.

A dot-map approach was used to display total loading estimates. Each dot on the map represents a specified number of tons. Each dot is randomly placed within a county. Dots are placed using ESRI's ArcMap non-fixed placement method (see ESRI publication Using ArcMap).

Surface water runoff, percolation, and evapotranspiration

Modeling the hydrologic cycle

Water is a potent force that interacts with or drives almost all environmental processes acting within an agricultural production system. There are six processes at work in the hydrologic cycle: condensation, precipitation, infiltration, runoff, evaporation, and transpiration.

The EPIC model simulates the hydrologic processes that operate at the field scale, with some simplifications. Evaporation and transpiration are combined into a single variable. Infiltration is partitioned into vertical and lateral flow, which results in changes in the soil-water storage. In reality, surface water runoff, infiltration, and evaporation occur simultaneously; in the EPIC model, however, surface water runoff occurs first, and only the portion that does not run off is available for infiltration or evapotranspiration (ET). EPIC models the hydrologic cycle only within the boundaries of a small field with a homogenous soil having a uniform slope. Ponding of water on the field is not simulated.

Given daily rainfall, surface runoff is estimated as a function of soil attributes, soil-water content, slope, land use and vegetative cover, antecedent moisture conditions, and management factors using a set of equations based on the NRCS curve number method (Mockus 1972). Each day the final estimate of the NRCS curve number is generated stochastically to account for the uncertainty of the deterministic estimate. Provisions are also made to reflect increases in runoff on frozen soils. For irrigation water, runoff was set as a fixed percent of the quantity applied; 5 percent is assumed to run off for sprinkler systems and 20 percent is assumed to run off for gravity or furrow applications.

Precipitation and irrigation water not removed from the field by surface water runoff is assumed to infiltrate into the soil. Vertical movement is simulated in EPIC using a storage routing technique that can be visualized as several vertically stacked buckets—each almost full of water. Rain fills and then overfills the top bucket which spills the excess into the bucket directly below, and so on. As infiltration occurs, soil water content in the top soil layer increases. When field capacity in a layer is exceeded, flow occurs vertically down through the soil layers and laterally off-field until the soil-water storage in that layer returns to field capacity. In each layer, vertical and lateral flows are calculated using flow rates estimated from travel times and the quantity of excess soil-water. Travel time for the vertical component (percolation) is a function of soil characteristics including porosity and saturated conductivity (or percent clay), while lateral subsurface flow is a fractional proportion of percolation estimated using the surface slope. Calculations for both flow components are performed simultaneously to avoid one dominating the other simply because of solution order. Interflow, the flow path in which lateral flow returns to the surface, is not considered in EPIC. Tile and surface drainage systems are also not taken into account in EPIC model simulations conducted for this study, as explained in a previous section.

Routines in EPIC alter water movement in certain cases. For instance, vertical routing usually moves water downward, but water can be routed upwards through capillary processes in cases where soil water exceeds storage capacity in a lower layer having a low saturated conductivity. Also, freezing temperatures can affect percolation because water is routed into a frozen layer but is not allowed to percolate out.

ET is the process that returns water vapor to the atmosphere by evaporation from the soil and transpiration by plants. EPIC estimates ET by first calculating the total quantity that could be transported under ideal circumstances, called potential evapotranspiration (PET). In these simulations, PET was estimated as a function of solar radiation and air temperature using the modified Hargreaves equation option in EPIC. PET is then partitioned into evaporation from soils and transpiration from plants using leaf area index and soil albedo. Actual plant water transpiration is some fraction of the potential, based upon leaf area index and soil water content. Actual soil water evaporation is some fraction of the potential, which is limited by exponential functions of soil depth and water content. Actual evaporation and transpiration are summed and reported as ET.

Land use decisions, field operations, and other management activities influence hydrology mainly by al-

tering field characteristics, such as surface roughness or residue cover, that affect surface storage, infiltration, or runoff. EPIC simulates the effects of these management activities; for example, the EPIC tillage component mixes nutrients and crop residues within the plow depth, simulates changes in soil bulk density, converts standing residue to flat residue, and simulates ridge height and surface roughness. Other land use and conservation practices are simulated using the curve number and associated functions. The effects of management on the hydrologic response vary from field to field based on the inherent properties of each field.

Model simulation results for water inputs

The model simulates precipitation and irrigation water inputs, as explained in previous sections. Overall, precipitation for non-irrigated acres averaged 32 inches per year and 27 inches per year for irrigated acres (table 20). On average, irrigated acres received an additional 18 inches per year throughout the growing season. Precipitation was much lower in arid and semi-arid areas, averaging about 13 inches per year; irrigation water use in arid areas averaged 23 inches per year. In the most humid regions, precipitation averaged about 55 inches per year on cropland acres. Total water inputs were highest in the South Central region (51 in/yr) and the Southeast region (47 in/yr), and lowest in the Northern Great Plains region (21 in/yr) (table 21).

The spatial distributions of precipitation and irrigation water inputs as simulated by the model are shown in maps 5 and 6. Because weather inputs were the same within each climate zone, the precipitation map (map 5) is a reflection of the underlying climate zones. Irrigation water was applied in the model simulations only on the acres that the NRI indicated were irrigated; thus the irrigation map (map 6) reflects the spatial distribution of irrigated acres. The values for irrigation water shown in map 6 are the average over all cropland acres in each map cell, and do not reflect the rates applied only on the irrigated acres within the map cell. For example, the yellow areas in map 6 have, on average over all cropland acres, 1 inch or less of irrigated water applied. The amount of irrigation water applied to the acres that were irrigated within those map cells, however, would have been similar to amounts reported for irrigated acres in tables 20 and 21.

Table 20 Summary of model simulation results for the hydrologic cycle (average annual values)

Precipitation class*	Water inputs				Evapotranspiration		Surface water runoff		Percolation		Subsurface lateral flow	
	Percent acres	Precipitation (in)	Irrigation (in)	Precipitation and irrigation (in)	Inches	Percent of inputs	Inches	Percent of inputs	Inches	Percent of inputs	Inches	Percent of inputs
Irrigated cropland												
Arid	4.4	12	23	36	32	88.7	3.2	8.9	0.8	2.2	0.10	0.3
Semi-arid	4.3	20	18	39	33	85.4	3.7	9.5	1.9	4.8	0.15	0.4
Sub-humid	1.1	33	11	43	32	73.6	5.6	12.9	5.7	13.1	0.17	0.4
Moderately humid	2.2	49	14	63	36	57.2	12.9	20.4	13.8	21.9	0.13	0.2
Humid	1.4	56	16	72	39	54.9	16.6	23.2	14.8	20.6	0.14	0.2
All	13.4	27	18	45	34	74.1	6.5	14.2	5.1	11.1	0.13	0.3
Non-irrigated cropland												
Arid	4.8	14	0	14	13	96.3	0.4	2.8	0.1	0.5	0.05	0.4
Semi-arid	24.2	20	0	20	19	92.2	1.3	6.1	0.3	1.6	0.07	0.3
Sub-humid	36.1	33	0	33	26	76.9	4.7	14.1	2.8	8.4	0.21	0.6
Moderately humid	18.8	44	0	44	29	65.1	7.1	16.1	7.8	17.7	0.30	0.7
Humid	2.6	55	0	55	32	58.5	11.0	19.8	11.4	20.5	0.24	0.4
All	86.6	32	0	32	24	75.6	4.2	13.3	3.3	10.4	0.18	0.6
Totals	100.0	31.1	2.5	33.5	25.3	75.3	4.5	13.5	3.5	10.6	0.2	0.5

*Precipitation classes: arid is less than 400 millimeters (<15.7 in); semi-arid is 400 to 700 millimeters (15.7–27.6 in); sub-humid is 700 to 1,000 millimeters (27.6–39.4 in); moderately humid is 1,000 to 1,300 millimeters (39.4–51.2 in); and humid is greater than 1,300 millimeters (>51.2 in).
Note: Precipitation classes were assigned to NRI sample points based on the 30-year average annual precipitation as simulated by EPIC.

Table 21 Water inputs, ET, surface water runoff, and percolation–by region and crop within regions (average annual values)

			Precip-itation	Irriga-tion	Total water inputs	Evapo-transpiration		Surface water runoff		Percolation		Subsurface lateral flow	
Region	**Crop**	**Acres (1,000s)**	**(in)**	**(in)**	**(in)**	**(in)**	**Percent of inputs**	**(in)**	**Percent of inputs**	**(in)**	**Percent of inputs**	**(in)**	**Percent of inputs**
Northeast	All crops	13,642	39.3	0.1	39.4	25.3	64.2	6.6	16.8	7.0	17.8	0.4	1.1
Northern Great Plains	All crops	72,397	18.7	2.6	21.3	19.5	91.6	1.5	6.9	0.3	1.4	0.1	0.4
South Central	All crops	45,350	47.9	3.1	51.1	32.3	63.2	10.1	19.7	8.4	16.5	0.2	0.4
Southeast	All crops	13,394	46.0	0.7	46.7	28.9	61.9	4.9	10.6	12.1	25.9	0.4	0.8
Southern Great Plains	All crops	32,096	21.2	5.7	26.9	24.4	90.6	1.6	6.0	0.9	3.2	0.1	0.3
Upper Midwest	All crops	112,581	33.8	0.2	34.0	25.8	75.8	4.8	14.1	3.2	9.3	0.2	0.6
West	All crops	9,018	12.6	19.7	32.3	26.9	83.1	3.9	12.0	1.5	4.6	0.1	0.3
All regions	All crops	298,478	31.1	2.5	33.5	25.3	75.3	4.5	13.5	3.5	10.6	0.2	0.5
By crop within region*													
Northeast	Corn	2,943	39.9	0.2	40.1	24.1	60.0	6.8	16.9	8.8	21.9	0.4	1.1
	Corn silage	1,482	38.6	<0.1	38.6	23.8	61.7	7.9	20.5	6.4	16.6	0.4	1.1
	Grass hay	2,369	38.8	<0.1	38.8	26.5	68.2	6.4	16.5	5.4	14.0	0.5	1.2
	Legume hay	4,052	38.2	<0.1	38.2	26.4	69.1	6.3	16.4	5.0	13.1	0.5	1.2
	Oats	362	38.5	<0.1	38.5	24.9	64.7	6.7	17.3	6.4	16.6	0.5	1.3
	Soybeans	1,305	41.5	0.4	41.9	23.8	56.9	6.8	16.1	11.0	26.3	0.3	0.7
	Winter wheat	853	41.0	0.4	41.4	26.3	63.6	5.7	13.8	9.0	21.7	0.4	0.9
Northern Great Plains	Barley	3,243	16.8	0.5	17.3	16.2	93.7	1.0	5.9	<0.1	0.2	<0.1	0.3
	Corn	15,466	20.2	7.4	27.5	24.3	88.4	2.3	8.4	0.8	3.0	0.1	0.5
	Corn silage	810	19.4	5.0	24.3	21.3	87.7	2.3	9.5	0.6	2.6	0.1	0.5
	Grass hay	2,443	17.8	0.3	18.1	17.0	93.9	0.9	5.2	0.1	0.6	0.1	0.4
	Legume hay	6,152	18.2	5.5	23.7	21.6	91.0	1.7	7.1	0.3	1.5	0.1	0.4
	Oats	1,255	18.4	0.3	18.6	17.3	92.7	1.2	6.3	0.1	0.7	0.1	0.4
	Spring wheat	18,916	17.4	0.1	17.5	16.4	93.5	1.1	6.1	<0.1	0.3	0.1	0.3
	Sorghum	1,595	19.9	2.5	22.4	20.9	93.0	1.3	5.6	0.3	1.3	0.1	0.4
	Soybeans	9,562	20.6	1.6	22.2	20.1	90.6	1.8	8.1	0.3	1.3	0.1	0.4
	Winter wheat	12,748	18.0	1.2	19.2	18.2	94.8	0.9	4.5	0.1	0.4	0.1	0.3

Table 21 Water inputs, ET, surface water runoff, and percolation–by region and crop within regions (average annual values)—Continued

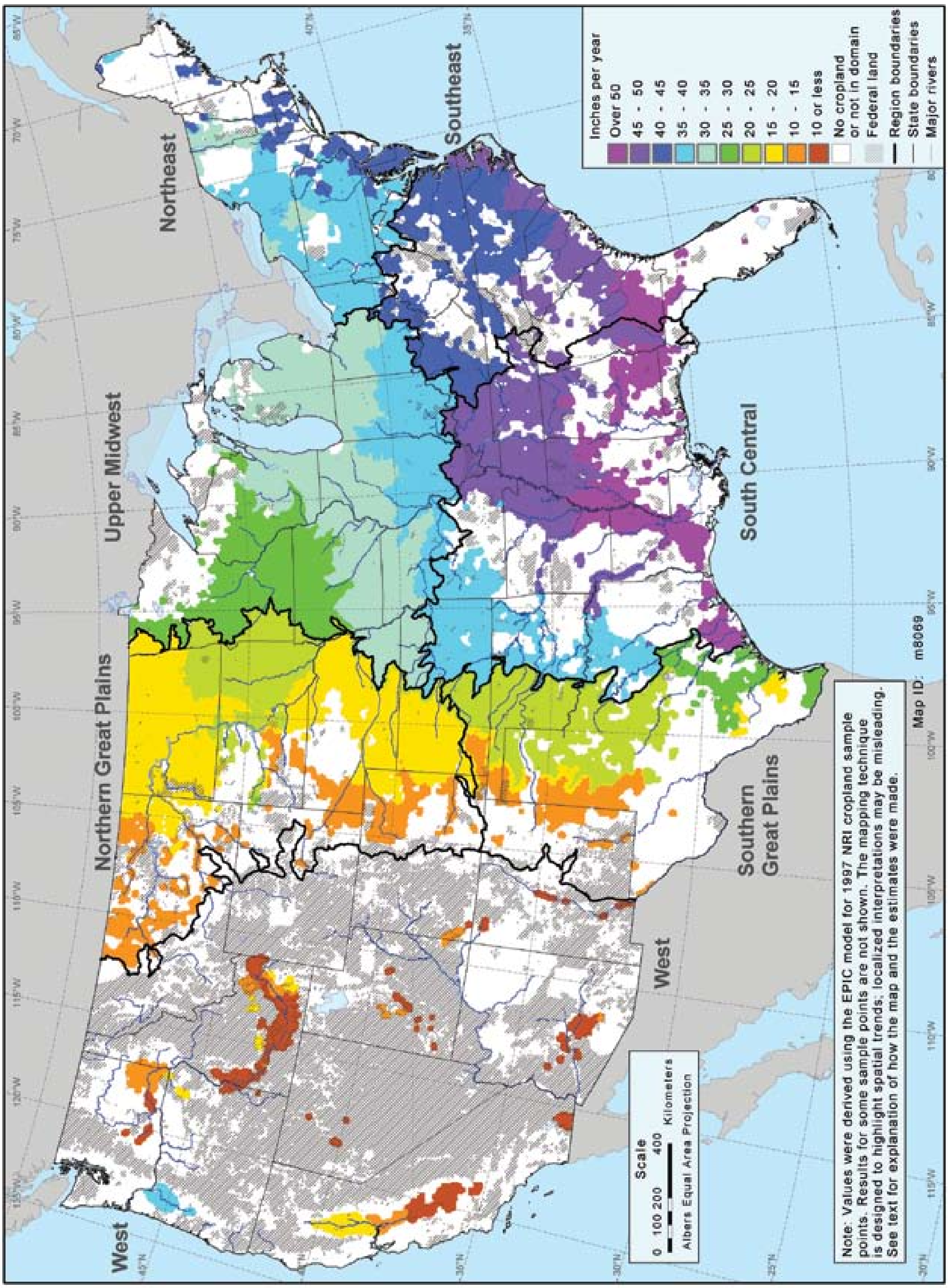
Region	Crop	Acres (1,000s)	Precip-itation (in)	Irriga-tion (in)	Total water inputs (in)	Evapo-transpiration (in)	Evapo-transpiration Percent of inputs	Surface water runoff (in)	Surface water runoff Percent of inputs	Percolation (in)	Percolation Percent of inputs	Subsurface lateral flow (in)	Subsurface lateral flow Percent of inputs
South Central	Corn	5,956	50.1	1.2	51.3	31.4	61.3	10.6	20.8	8.8	17.2	0.3	0.5
	Cotton	5,487	52.0	4.0	56.0	31.9	57.0	10.4	18.6	13.2	23.6	0.2	0.4
	Grass hay	3,347	46.0	<0.1	46.0	31.1	67.7	7.2	15.5	7.3	15.8	0.4	0.8
	Legume hay	1,630	45.5	0.3	45.7	33.1	72.3	7.0	15.2	5.2	11.3	0.4	0.9
	Peanuts	880	51.1	2.6	53.7	33.1	61.6	5.0	9.3	14.6	27.2	0.5	1.0
	Rice	3,004	53.3	23.1	76.4	37.2	48.7	19.4	25.4	19.5	25.5	0.1	0.1
	Sorghum	2,729	41.0	0.4	41.5	31.0	74.7	6.4	15.4	4.0	9.5	0.1	0.3
	Soybeans	14,083	50.2	2.6	52.8	32.9	62.3	12.2	23.1	7.4	14.0	0.2	0.3
	Winter wheat	7,896	40.8	0.5	41.4	31.1	75.2	5.8	13.9	4.4	10.6	0.2	0.4
Southeast	Corn	3,028	46.0	0.7	46.7	29.3	62.7	5.4	11.6	11.4	24.4	0.3	0.6
	Corn silage	412	44.2	0.1	44.3	28.0	63.1	7.2	16.2	8.5	19.2	0.5	1.2
	Cotton	2,422	48.2	1.9	50.0	27.9	55.8	4.3	8.6	16.5	32.9	0.3	0.7
	Grass hay	2,000	44.6	<0.1	44.6	30.4	68.0	4.6	10.3	8.9	20.1	0.6	1.3
	Legume hay	1,183	42.6	<0.1	42.6	31.4	73.8	5.8	13.6	4.8	11.3	0.5	1.2
	Peanuts	479	48.9	2.4	51.3	31.9	62.2	4.4	8.5	13.2	25.7	0.4	0.8
	Soybeans	2,419	46.3	0.4	46.6	28.4	60.8	4.9	10.5	12.8	27.5	0.3	0.7
	Winter wheat	1,216	45.8	0.6	46.4	25.8	55.7	4.3	9.3	15.6	33.7	0.4	0.9
Southern Great Plains	Corn	2,665	20.8	13.1	33.9	30.2	89.2	2.8	8.3	0.7	2.2	0.1	0.3
	Cotton	7,316	19.9	8.5	28.4	24.9	87.8	1.9	6.8	1.5	5.4	0.1	0.2
	Legume hay	677	18.5	18.5	36.9	33.8	91.6	2.2	6.0	0.6	1.8	0.2	0.5
	Oats	503	26.8	0.6	27.4	22.8	83.2	3.1	11.5	1.4	5.2	0.1	0.3
	Peanuts	484	22.9	8.8	31.7	27.1	85.4	2.1	6.7	2.3	7.3	0.2	0.5
	Sorghum	4,895	22.2	3.9	26.0	23.3	89.6	2.0	7.8	0.6	2.4	0.0	0.2
	Winter wheat	15,037	21.4	3.1	24.5	22.8	93.3	1.0	4.2	0.6	2.3	0.1	0.3

Table 21 Water inputs, ET, surface water runoff, and percolation–by region and crop within regions (average annual values)—Continued

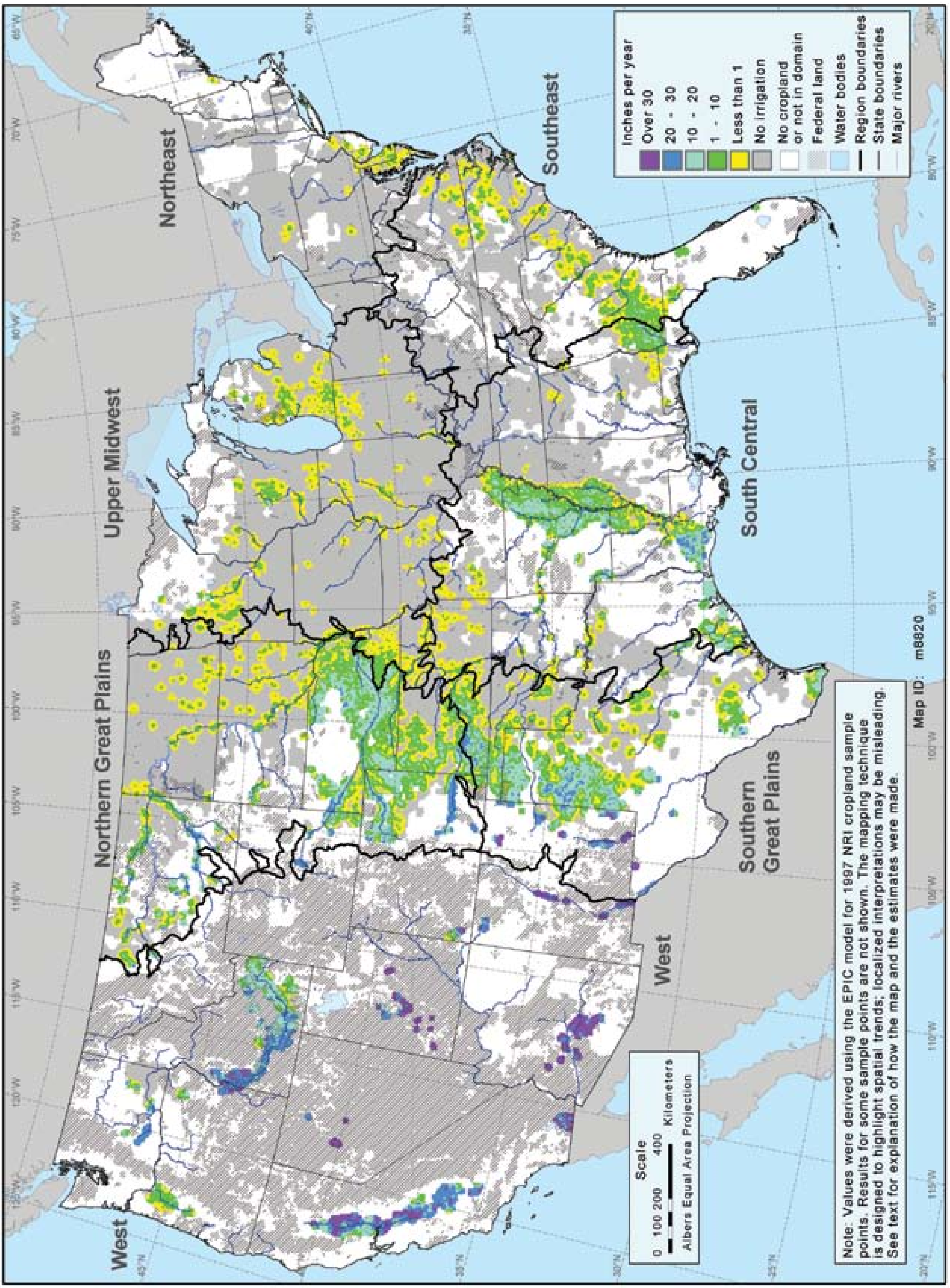
			Precip-itation	Irriga-tion	Total water inputs	Evapo-transpiration		Surface water runoff		Percolation		Subsurface lateral flow	
Region	**Crop**	**Acres (1,000s)**	**(in)**	**(in)**	**(in)**	**(in)**	**Percent of inputs**	**(in)**	**Percent of inputs**	**(in)**	**Percent of inputs**	**(in)**	**Percent of inputs**
Upper Midwest	Corn	47,941	34.0	0.3	34.3	25.8	75.1	4.8	14.1	3.5	10.1	0.2	0.6
	Corn silage	1,947	31.4	0.1	31.5	22.6	71.7	5.3	16.9	3.4	10.8	0.2	0.7
	Grass hay	4,044	33.8	<0.1	33.8	26.9	79.8	4.3	12.8	2.1	6.3	0.3	0.8
	Legume hay	9,233	32.2	0.1	32.3	25.5	78.9	4.2	13.1	2.2	6.9	0.3	0.9
	Oats	1,388	31.0	0.1	31.1	24.2	77.9	3.9	12.4	2.7	8.7	0.3	0.9
	Spring wheat	815	27.0	<0.1	27.0	23.7	87.9	2.9	10.6	0.3	1.2	0.0	0.2
	Sorghum	1,604	33.2	0.2	33.4	27.7	82.9	3.6	10.8	1.8	5.4	0.2	0.7
	Soybeans	40,049	34.3	0.2	34.4	25.7	74.6	5.1	14.8	3.4	9.9	0.2	0.5
	Winter wheat	5,147	34.9	0.1	35.0	28.3	81.0	4.6	13.2	1.8	5.0	0.2	0.5
West	Barley	958	12.0	8.8	20.7	18.5	89.0	1.9	9.1	0.3	1.3	0.1	0.6
	Corn silage	297	14.5	21.9	36.4	28.7	79.0	4.3	11.9	3.2	8.8	0.1	0.3
	Cotton	1,631	10.1	31.3	41.3	36.0	87.0	4.7	11.4	0.6	1.4	0.0	0.1
	Legume hay	1,847	10.1	28.9	39.0	33.0	84.6	4.8	12.2	1.1	2.8	0.1	0.3
	Potatoes	329	10.5	14.6	25.1	22.8	90.7	2.1	8.3	0.2	0.7	0.1	0.4
	Rice	599	17.1	34.6	51.6	36.7	71.0	9.4	18.3	5.5	10.6	0.0	0.1
	Spring wheat	772	11.5	11.0	22.5	20.0	88.9	2.0	8.7	0.4	1.9	0.1	0.5
	Winter wheat	2,118	15.7	8.7	24.4	19.4	79.4	2.7	11.0	2.2	8.9	0.2	0.7

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Map 5 Average annual precipitation input for model simulations



Map 6 Average annual irrigation input for model simulations



Model simulation results for surface water runoff, percolation, and ET

EPIC estimates the amount of water inputs that leaves the field through ET, surface runoff, percolation, and subsurface lateral flow. Model results for surface water runoff and percolation are key to understanding the estimates of potential pollutants from farm fields presented in subsequent sections.

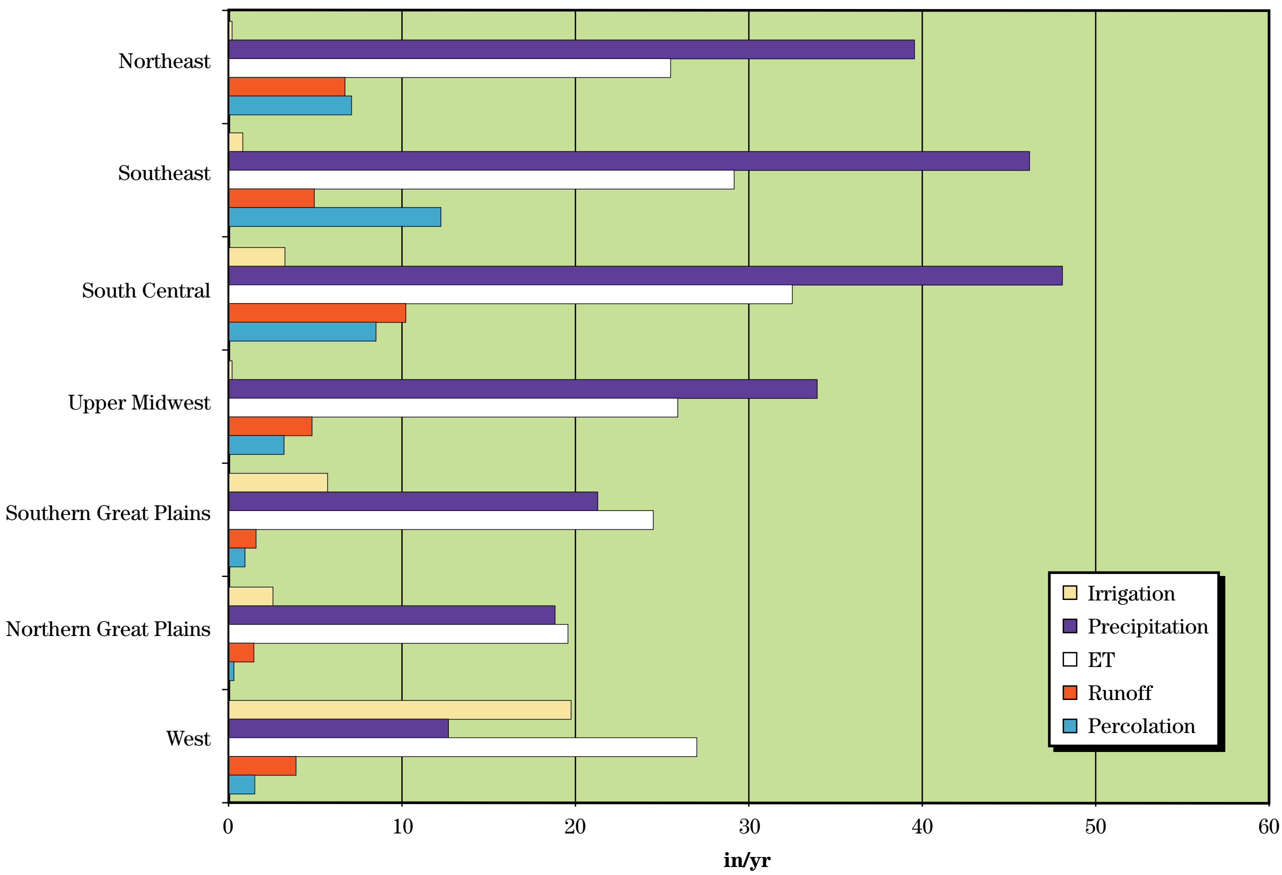
Most of the water that falls on farm fields or is added through irrigation passes back to the atmosphere through evaporation and transpiration (fig. 8). Model simulation results showed that on average about 75 percent of water inputs for cropland results in ET (tables 20 and 21). The percent of water inputs that result in ET is lower in areas where precipitation is higher, averaging 55 to 65 percent in moderately humid and humid cropland regions. In arid and semi-arid cropland regions, more than 90 percent results in ET on non-irrigated acres and more than 80 percent on irrigated acres. These results are consistent with research that shows that plants transpire a larger proportion of available water in arid regions (Garbrecht et al. 2004).

Model simulation results showed that the remainder of the water inputs—ranging from 8 to 38 percent among the seven regions (table 21)—results in either percolation or surface water runoff. A minor amount (less than 1% in most cases) leaves the field through subsurface lateral flow, which may either eventually return to the surface and discharge into a receiving water body or continue to percolate downward once a more porous soil is encountered. Nationally, surface water runoff is higher than percolation, averaging about 4.5 inches per year compared to 3.5 inches per year for percolation. At the regional scale, however, average percolation was higher than average surface water runoff in two regions—the Northeast and Southeast regions. For cropland acres in the Southeast region, percolation was more than twice the amount of surface water runoff (table 21).

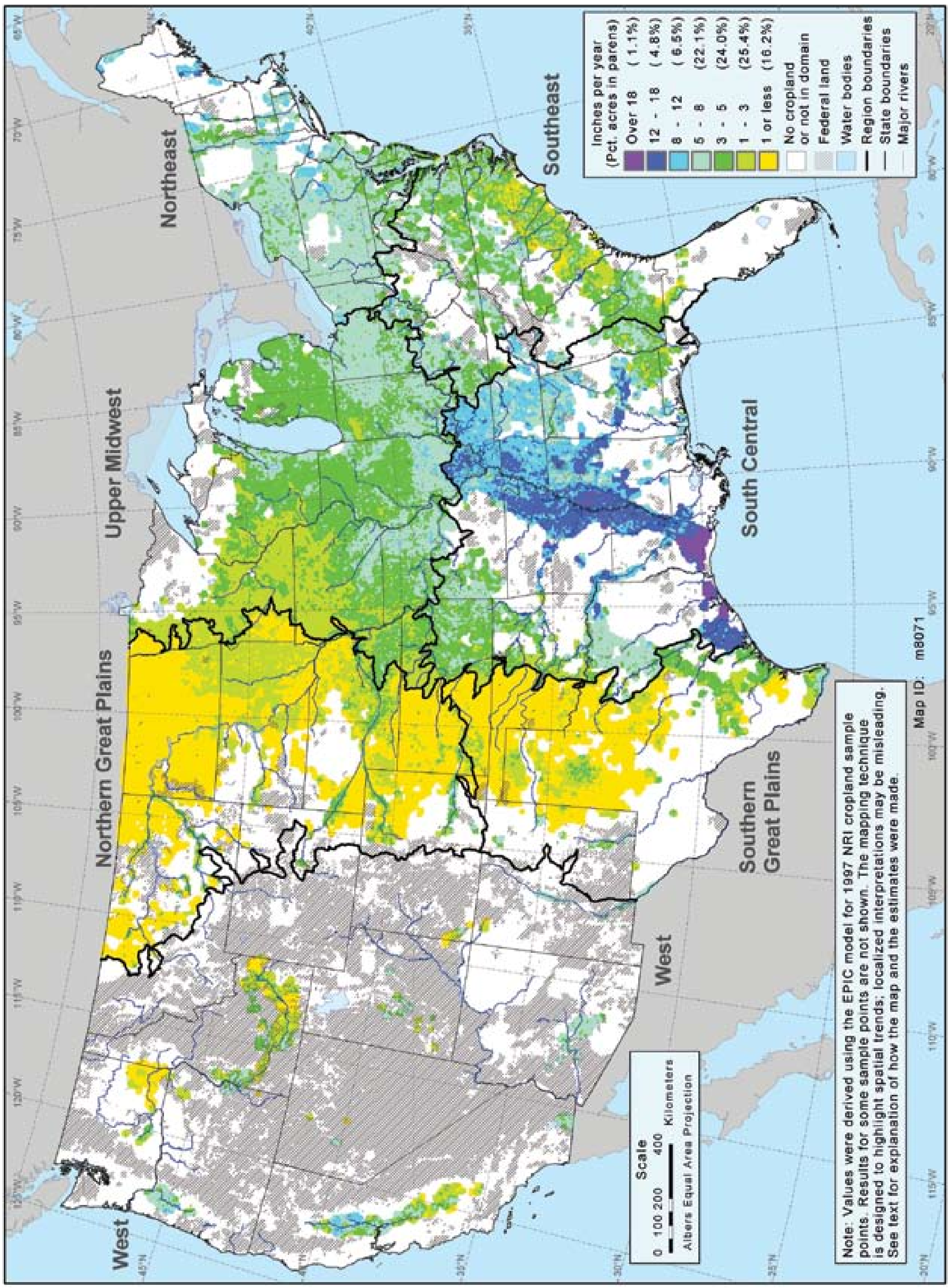
Spatial trends in surface water runoff and percolation are shown in maps 7 and 8. The cropland areas with the highest surface water runoff are found along the lower half of the Mississippi River Basin and portions of southeast Texas. While this area also had fairly high percolation, the highest percolation for cropland was in the eastern coastal plain extending from southern Alabama northward through the Delmarva Peninsula. The relationship between water inputs, surface water runoff, and percolation on cropland differs throughout the country, reflecting interactions between climate, soil and terrain characteristics, and agricultural practices.

Although the principal determinant of surface water runoff and percolation is precipitation and irrigation water use, management activities and soil characteristics can also have a pronounced influence on field hydrology.

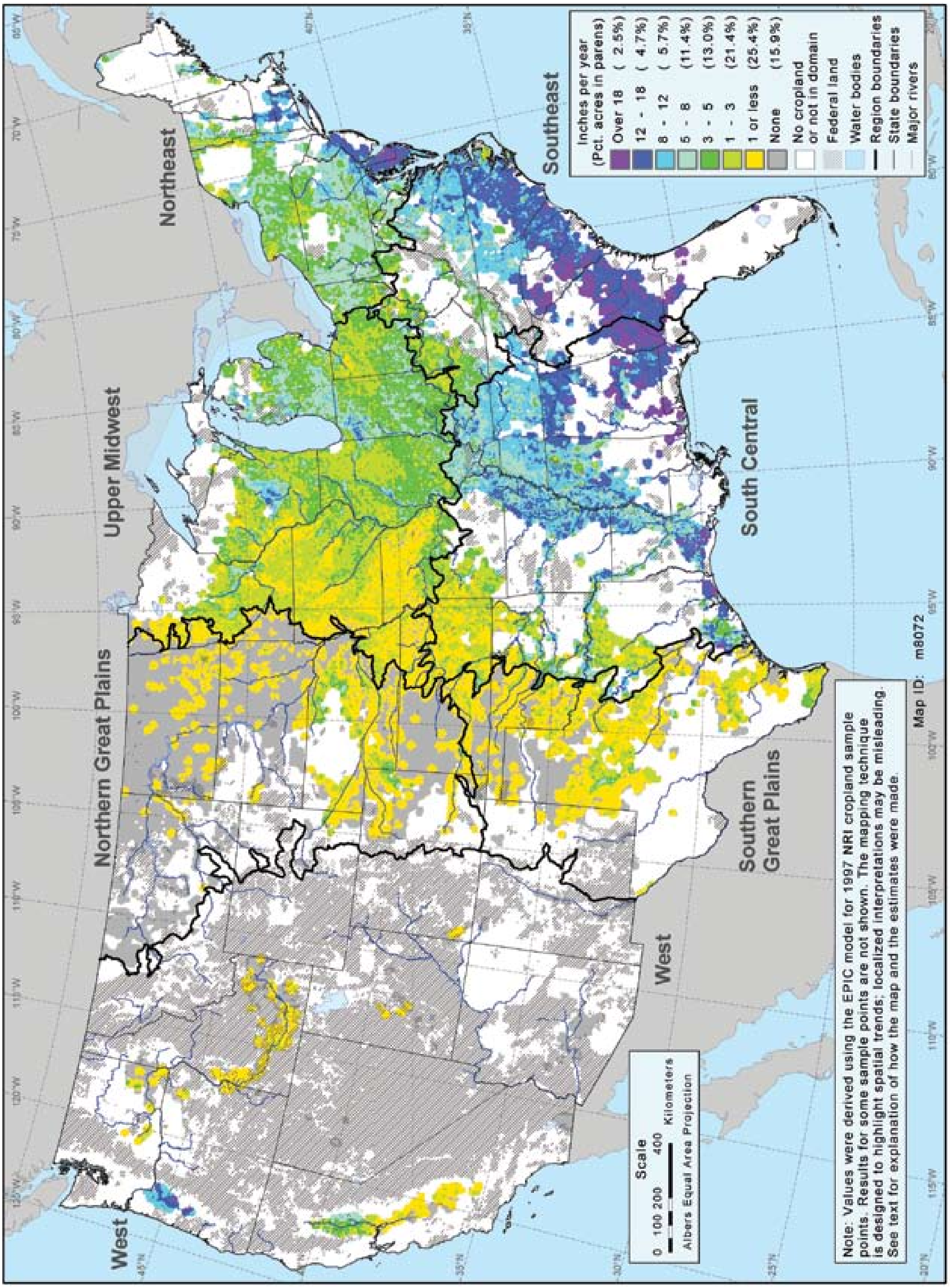
Figure 8 Average water inputs, ET, surface water runoff, and percolation–by region



Map 7 Estimated average annual surface water runoff



Map 8 Estimated average annual percolation



Sediment loss from water erosion

Modeling sediment loss

Water erosion is the detachment and transport of soil particles by rainfall or irrigation water. When precipitation events occur, raindrops break the bond between soil particles and displace them. Sheet erosion takes place when the dislodged soil particles are moved by thin sheets of water flowing over the surface. Rill erosion occurs when the surface flow of water establishes paths and the flowing water detaches soil particles from the sides and bottoms of the rills that are formed. Ephemeral or concentrated-flow erosion follows when the topography of a landscape is such that rills enlarge and join with others to form channels. When concentrated-flow erosion is allowed to continue over time, it results in gully erosion, which is the most severe form of water erosion found on cropland.

The interaction between weather, soil properties, and farming practices (including irrigation) determines the rate of soil erosion. The amount of rainfall and the rainfall intensity are primary determinants of water erosion under rain-fed conditions. Irrigation induced erosion is primarily determined by the velocity of the water flowing through the furrows or basin and the volume and intensity of the water applied during sprinkler irrigation. The inherent potential for soil to erode is determined by the slope and topography of the land, the texture and structure of the soil, and the organic matter content in the soil. Soil texture refers to the proportions of particles of sand, silt, and clay in the soil. Water moves detached clay particles more readily than particles of silt or sand, but clay particle bonds are also stronger than those of silt and sand. Soil structure refers to how the soil particles are clustered in aggregates, which are held together by physical and chemical bonds. The shape, size, and arrangement of aggregates determine the pathways of infiltrating water and the volume of air space between aggregates. The more air space within a soil, the more room it has for infiltrating water. Reduced infiltration leads to more runoff, and thus more water erosion. Strong bonds and large aggregates provide more resistance to erosive forces. Organic matter enhances soil structure and increases water infiltration, thereby reducing the potential for water erosion. Plant cover and crop residue also reduce the potential for water erosion.

The EPIC model simulates sheet and rill erosion processes. The current version of EPIC includes six alternative water erosion prediction equations that represent different methods of accounting for erosion and net sediment delivery from the field. For this study, the Modified Universal Soil Loss Equation (MUSLE) was selected for reporting sediment delivery. MUSLE accounts for the amount of eroded soil that leaves the field through the processes of sheet and rill erosion. MUSLE does not include soil loss that can occur through ephemeral gully or gully erosion processes or erosion of furrows or basins during gravity irrigation events.

MUSLE is a modification of the Universal Soil Loss Equation (USLE). USLE is an estimate of sheet and rill soil movement down a uniform slope using rainfall energy as the erosive force acting on the soil (Wischmeier and Smith 1978). Depending on soil characteristics (texture, structure, organic matter, and permeability), some soils erode easily while others are inherently more resistant to the erosive action of rainfall.

MUSLE is similar to USLE except for the energy component. USLE depends strictly upon rainfall as the source of erosive energy. MUSLE uses storm-based runoff volumes and runoff peak flows to simulate erosion and sediment yield (Williams 1995). The use of runoff variables rather than rainfall erosivity as the driving force enables MUSLE to estimate sediment yields for individual storm events. The water erosion model uses an equation of the form:

$$Y = X \times EK \times CVF \times PE \times SL \times ROKF$$

where:

Y = sediment yield in tons per hectare
EK = soil erodibility factor
CVF = crop management factor that captures the relative effectiveness of soil and crop management systems in preventing soil loss
PE = erosion control practice factor (including management practices such as terraces, contour farming, and stripcropping)
SL = slope length and steepness factor
ROKF = coarse fragment factor

For estimating MUSLE, the energy factor, X, is represented by:

$$X = 1.586 \times \left(Q \times q_p\right)^{0.56} \times WSA^{0.12}$$

where:
- Q = runoff volume in millimeters
- q_p = peak runoff rate in millimeters per hour
- WSA = watershed area in hectares

Runoff volume is estimated using the SCS curve number method. Peak flow was estimated using a modification of the rational method which relates rainfall to peak flow on a proportional basis. The rational equation is:

$$q = C \times i \times A$$

where:
- q = peak flow rate
- C = runoff coefficient representing watershed characteristics
- i = rainfall intensity for the watershed's time of concentration
- A = watershed area

See Williams (1995) for details on the erosion and sediment yield equations used in EPIC.

Irrigation induced erosion was estimated for furrows and flat surfaces using flow as the driving force. For furrows, erosion is a function of irrigation application rate, flow velocity (calculated using Manning's equation), the soil erodibility factor, and sediment concentration. Erosion from flat surfaces was calculated with the MUSLE using the irrigation application volume and irrigation runoff rate to estimate the energy component.

To estimate MUSLE, the drainage area must be specified. For this study, the drainage area was set equal to 1 hectare (2.47 a). A 1-hectare drainage area was used to be consistent with other modeling assumptions tailored to the NRI sample point, such as uniform field slope, uniform precipitation, homogeneous soils, and management activities assumed to be evenly applied throughout a field.

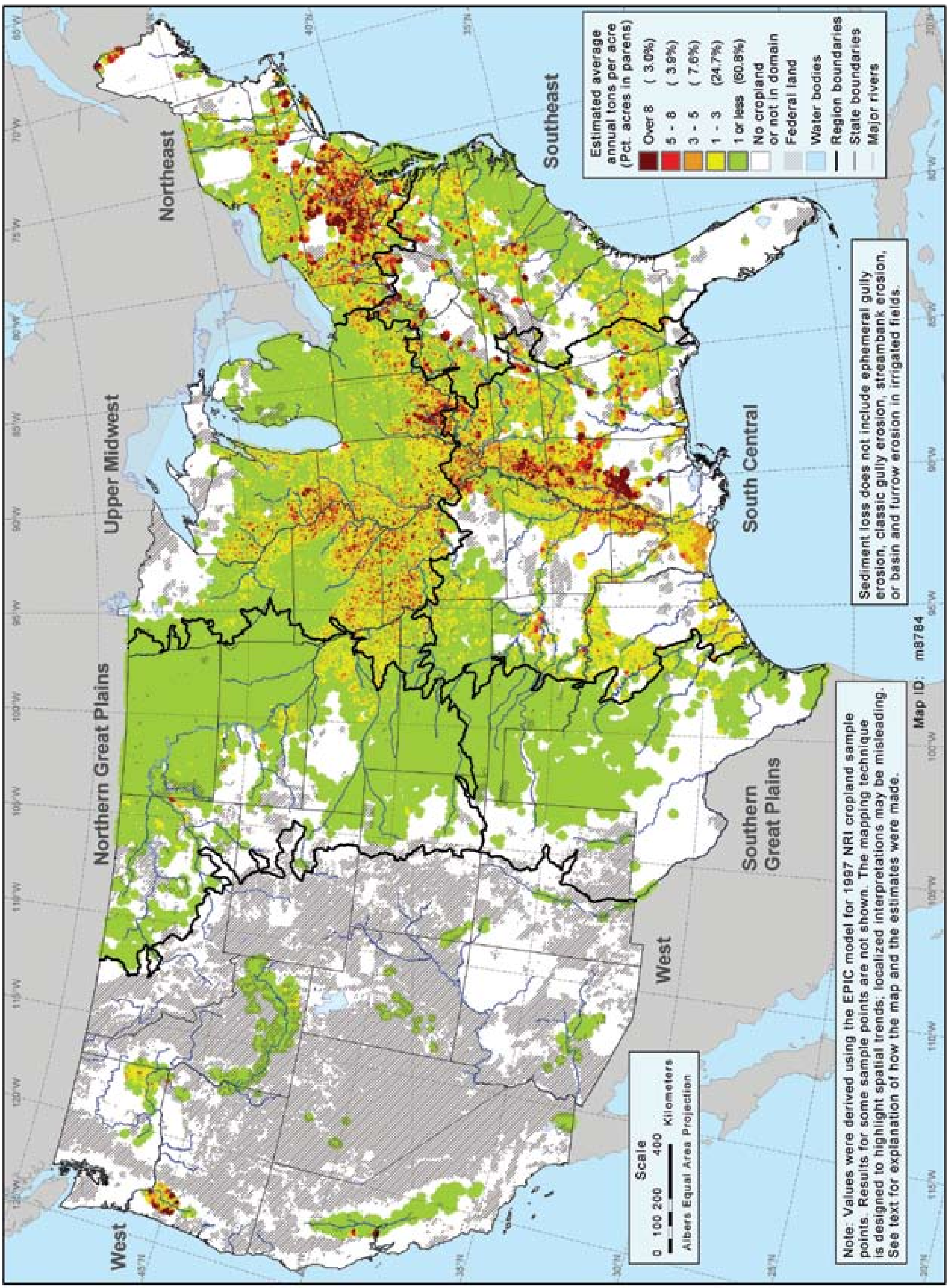
MUSLE produces estimates of sediment yield by calculating the tons of soil lost through sheet and rill erosion processes on a daily basis and summing these daily estimates to obtain the total tons of sediment yield per acre per year. MUSLE includes sheet and rill erosion that occurs when precipitation is sufficient to result in surface water runoff. It is possible for a light rainfall to cause some sheet and rill erosion, but not result in surface water runoff from the field; MUSLE does not include this source of sheet and rill erosion. This estimate of sediment yield is referred to throughout this report as sediment loss.

EPIC requires that only one of the six water erosion prediction equations be chosen as the driving equation that changes the soil profile and soil properties over time as erosion occurs. For this study, MUST, the theoretical erosion and sedimentation equation, was used as the driving equation. MUST is an equation developed on the basis of sediment concentrations (Williams 1995). Similar to MUSLE, MUST provides better estimates of nitrogen and phosphorus losses with sediment than use of USLE or MUSLE as the driving erosion equation. MUST differs from MUSLE in that the drainage area is not a factor in the equation.

Model simulation results for sediment loss

Model simulations on the cropland acres included in this study show that sediment loss from sheet and rill erosion processes on cropland varies depending on the region of the country (reflecting climatic and hydrologic factors), the crop type and related farming practices, the presence of conservation practices, and characteristics of the soil. Map 9 shows the cropland areas of the country that have the highest potential for sediment loss. The most vulnerable cropland acres—shown in dark red and red on the map—had average sediment loss estimates greater than 5 tons per acre per year and represent about 7 percent of the cropland acres. Another 8 percent of the acres had average sediment loss estimates between 3 and 5 tons per acre per year, shown in orange on the map. These acres are mostly collocated with the most vulnerable acres. About 25 percent of the cropland acres had average sediment loss estimates between 1 and 3 tons per acre per year, usually found in broad areas surrounding the most vulnerable acres. The remaining 60 percent of the cropland acres had average sediment loss estimates less than 1 ton per acre, shown on the map in green. These least vulnerable acres tend to correspond to areas shown in map 7 where surface water runoff is less than about 3 inches per year.

Map 9 Estimated average annual per-acre sediment loss (MUSLE)



The most vulnerable areas with respect to sediment loss on a per-acre basis tend to be concentrated in five areas of the country:

- an area in central and southeastern Pennsylvania and northern Maryland associated primarily with the Lower Susquehanna Basin and Potomac River Basin
- an area that follows the Ohio River from southern Illinois through western Pennsylvania
- an area along the lower Mississippi, primarily the eastern part of the drainage area
- an area that extends along the upper Mississippi, including the northern drainage area of the Missouri River in northern Missouri and southwest Iowa
- the Willamette River Basin in the Northwest

Per-acre sediment loss estimates

The average sediment loss rate for all cropland acres represented in the study was 1.5 tons per acre per year (table 22). Sediment loss per acre was greatest in the Northeast and the South Central regions, where sediment loss estimates averaged about 3 tons per cropland acre per year. Sediment loss per acre was lowest in the Great Plains regions and the West, averaging less than 0.6 tons per cropland acre per year.

The crops associated with the highest average sediment loss estimates were generally corn silage, corn, and cotton; although, average estimates by crop varied substantially from region to region (table 22; fig. 9). Averaged over all regions, corn silage had the highest sediment loss rate at nearly 6 tons per acre, and had the highest average sediment loss rate of all crops in most of the regions. Alfalfa hay had the lowest sediment loss rate (nearly zero), followed by spring wheat. All crops grown in the Northeast region had the highest per-acre sediment loss estimates of any region.

Most irrigated crops had about the same sediment loss estimates as non-irrigated crops in the same region (table 23). The largest differences occurred for wheat and barley acres in the West region and corn and cotton acres in the South Central region. Sediment loss estimates for these crops averaged about 2 tons per acre per year less for irrigated crops than for non-irrigated crops. Lower sediment loss for irrigated acres is generally expected because irrigation water is usually applied during the growing season when the ET rate is high, antecedent soil moisture is relatively low, and crop cover and surface residues provide some protection of the soil surface from the forces of erosion. Higher sediment loss estimates for irrigated acres than for non-irrigated acres, when it occurs, is due to more overall water inputs on irrigated acres in arid areas as well as climatic and soil type differences between irrigated and non-irrigated acres within a region.

Tons of sediment loss

When the acres of cropland are taken into account, three-fourths of the total tons of sediment loss for all cropland is associated with two regions—the Upper Midwest region and the South Central region (table 22; map 10). With average sediment loss estimates above the national average, the total sediment loss from cropland acres in these two regions was disproportionately high, relative to the percent of cropland acres. The South Central region contains 15 percent of the cropland acres included in the study but accounts for 27 percent of the total tons per year of sediment loss from cropland. Similarly, the Upper Midwest region contains 38 percent of the cropland acres but accounts for 48 percent of the total sediment loss. Sediment loss in the Northeast region was also disproportionately high; the Northeast accounted for about 9 percent of the total sediment loss from cropland but accounted for only about 5 percent of the cropland acres.

In terms of total sediment loss, corn and soybeans accounted for about two-thirds of the total for all cropland (table 22). In the Northeast region, corn and corn silage accounted for most of the sediment loss in the region. Cotton accounted for the most sediment loss in the Southeast and the South Central regions; the average loss rate for cotton in the South Central region was nearly 7 tons per acre. Corn accounted for the most sediment loss in the Upper Midwest and the Northern Great Plains regions, although average per-acre sediment loss estimates for corn in those regions were not as high as in the Northeast or the South Central regions. In the Southern Great Plains and the West, winter wheat accounted for more total sediment loss than other crops.

Effects of soil properties on sediment loss

Soil properties such as hydrologic soil group and soil texture have a pronounced influence on the potential for sediment loss to occur. The mix of hydrologic soil groups and soil textures varies throughout the

Table 22 Sediment loss (MUSLE) estimates–by region and by crop within regions (average annual values)

Region	Crop	Acres (1,000s)	Tons per acre per year	Tons per year (1,000s)
By region				
Northeast	All crops	13,642	3.2	43,467
Northern Great Plains	All crops	72,397	0.5	33,628
South Central	All crops	45,350	2.8	125,565
Southeast	All crops	13,394	1.6	21,520
Southern Great Plains	All crops	32,096	0.4	11,506
Upper Midwest	All crops	112,581	2.0	218,991
West	All crops	9,018	0.6	4,944
All regions	All crops	298,478	1.5	459,622
By crop within region*				
Northeast	Corn	2,943	5.2	15,304
	Corn silage	1,482	11.0	16,347
	Grass hay	2,369	1.4	3,208
	Legume hay	4,052	<0.1	4
	Oats	362	3.5	1,282
	Soybeans	1,305	2.8	3,707
	Winter wheat	853	2.8	2,423
Northern Great Plains	Barley	3,243	0.2	756
	Corn	15,466	0.8	13,091
	Corn silage	810	1.4	1,100
	Grass hay	2,443	0.1	249
	Legume hay	6,152	<0.1	32
	Oats	1,255	0.6	731
	Spring wheat	18,916	0.4	7,260
	Sorghum	1,595	0.6	909
	Soybeans	9,562	0.7	6,734
	Winter wheat	12,748	0.2	2,714
South Central	Corn	5,956	3.6	21,333
	Cotton	5,487	6.9	37,837
	Grass hay	3,347	1.4	4,529
	Legume hay	1,630	<0.1	1
	Peanuts	880	1.7	1,541
	Rice	3,004	2.9	8,624
	Sorghum	2,729	1.7	4,698
	Soybeans	14,083	2.2	31,555
	Winter wheat	7,896	1.7	13,598

Table 22 Sediment loss (MUSLE) estimates–by region and by crop within regions (average annual values)—Continued

Region	Crop	Acres (1,000s)	Tons per acre per year	Tons per year (1,000s)
Southeast	Corn	3,028	1.4	4,197
	Corn silage	412	6.7	2,746
	Cotton	2,422	2.4	5,832
	Grass hay	2,000	1.2	2,380
	Legume hay	1,183	<0.1	2
	Peanuts	479	1.8	861
	Soybeans	2,419	1.0	2,372
	Winter wheat	1,216	2.3	2,787
Southern Great Plains	Corn	2,665	0.6	1,588
	Cotton	7,316	0.4	3,083
	Legume hay	677	0.0	0
	Oats	503	0.6	310
	Peanuts	484	0.6	295
	Sorghum	4,895	0.4	1,826
	Winter wheat	15,037	0.3	4,289
Upper Midwest	Corn	47,941	2.6	126,254
	Corn silage	1,947	4.4	8,495
	Grass hay	4,044	0.5	2,034
	Legume hay	9,233	<0.1	4
	Oats	1,388	2.2	3,019
	Spring wheat	815	0.2	184
	Sorghum	1,604	2.0	3,155
	Soybeans	40,049	1.7	69,565
	Winter wheat	5,147	1.2	6,096
West	Barley	958	1.0	914
	Corn silage	297	0.5	140
	Cotton	1,631	0.2	282
	Legume hay	1,847	<0.1	21
	Potatoes	329	0.2	63
	Rice	599	0.3	164
	Spring wheat	772	0.5	401
	Winter wheat	2,118	1.3	2,812

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Figure 9 Sediment loss estimates (MUSLE)–by crop within regions

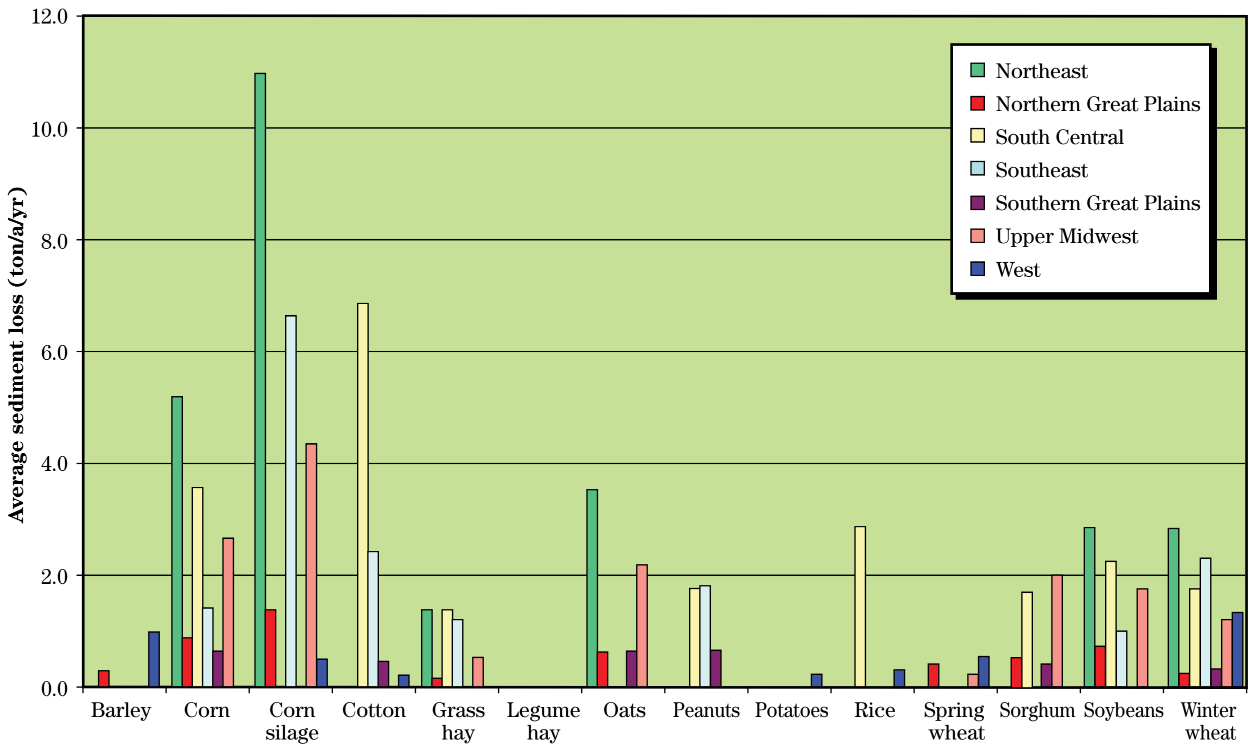
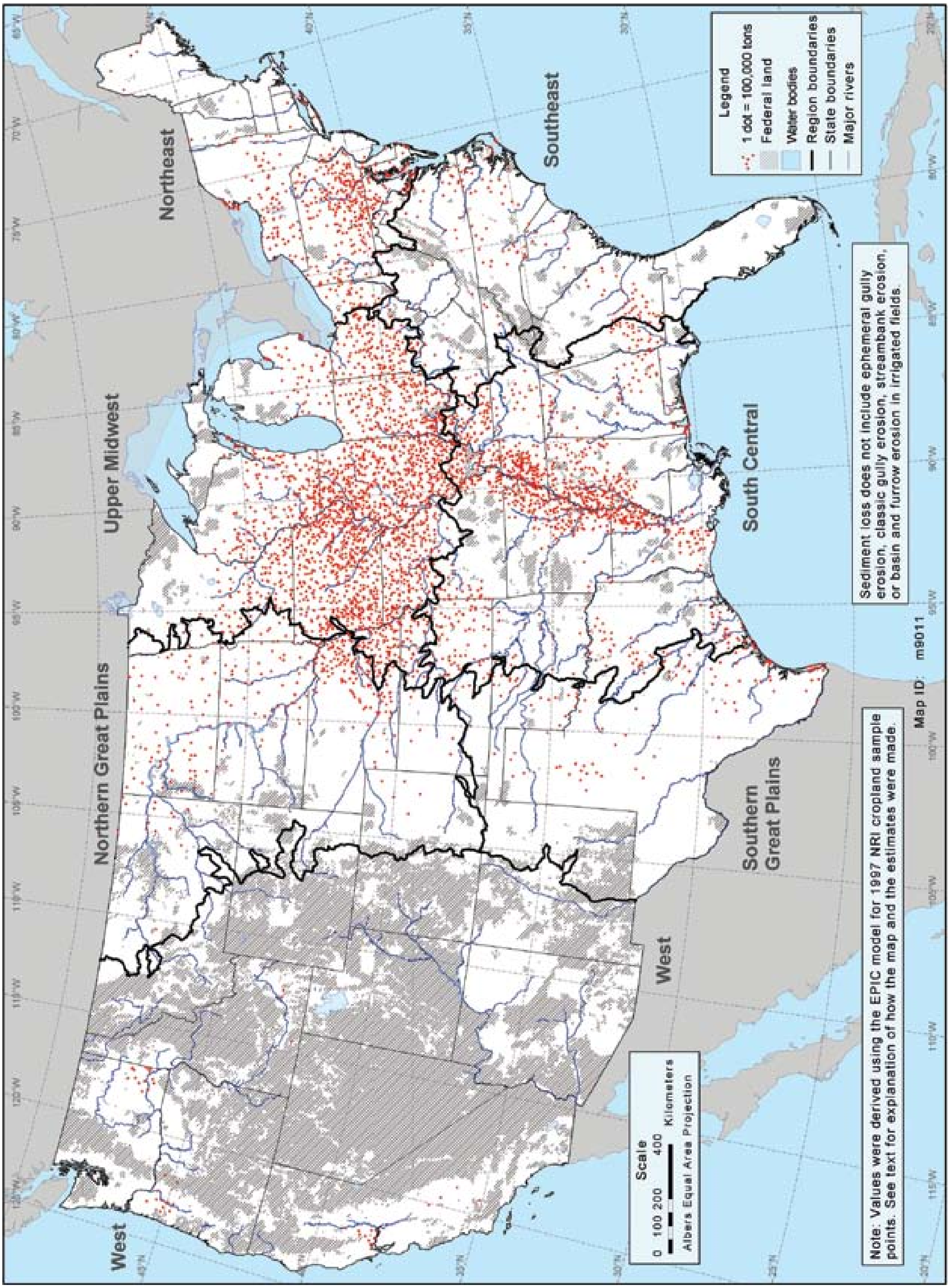


Table 23 Comparison of sediment loss estimates (MUSLE) for irrigated crops to estimates for non-irrigated crops (average annual values)

		Non-irrigated crops		Irrigated crops	
Region	**Crop***	**Acres (1,000s)**	**Tons per acre per year**	**Acres (1,000s)**	**Tons per acre per year**
Northern Great Plains	Corn	8,785	0.9	6,680	0.8
	Legume hay	4,816	<0.1	1,336	<0.1
	Soybeans	8,578	0.7	984	1.2
	Winter wheat	12,086	0.2	662	0.1
South Central	Corn	5,285	3.8	671	2.0
	Cotton	3,983	7.6	1,505	5.1
	Rice	0	NA	3,004	2.9
	Soybeans	10,498	2.3	3,585	2.0
	Winter wheat	7,341	1.7	554	1.8
Southeast	Cotton	2,115	2.4	307	2.7
Southern Great Plains	Corn	672	1.5	1,993	0.3
	Cotton	4,486	0.4	2,831	0.5
	Legume hay	263	<0.1	414	<0.1
	Peanuts	159	0.9	325	0.5
	Sorghum	3,748	0.4	1,147	0.3
	Winter wheat	13,046	0.3	1,991	0.1
Upper Midwest	Corn	46,424	2.7	1,517	1.6
	Soybeans	39,409	1.7	641	1.4
West	Barley	357	2.4	601	0.1
	Corn silage	0	NA	297	0.5
	Cotton	0	NA	1,631	0.2
	Legume hay	159	0.1	1,688	<0.1
	Potatoes	0	NA	329	0.2
	Rice	0	NA	599	0.3
	Spring wheat	197	1.8	575	0.1
	Winter wheat	1,066	2.1	1,052	0.5

* Irrigated crops with more than 250,000 acres in a region are included in the table. These 26 crop-region combinations represent 92 percent of the irrigated acres included in the study.
NA = not applicable.

Map 10 Estimated average annual tons of sediment loss (MUSLE)



country, contributing to the variability in the spatial distribution of sediment loss shown in map 9. As shown in figure 10, which presents average annual sediment loss estimates for all model simulations included in the study, the lowest sediment loss estimates were for hydrologic soil group A, which tend to be well-drained soils with high infiltration estimates. However, hydrologic group A soils represent less than 10 percent of the soils in all regions and only about 4 percent of all cropland acres included in the study. Soils in hydrologic soil group B, which is the dominant hydrologic soil group in most regions and represents the majority of cropland acres, had sediment loss estimates at or below the average of about 1.5 tons per acre per year for all soil texture classes. In contrast, average sediment loss estimates for hydrologic soil groups C and D exceeded the average of 1.5 tons per acre per year for nearly all soil textures. Hydrologic soil groups C and D represent 26 and 15 percent, respectively, of the cropland acres included in the study. The highest sediment loss estimates occurred for medium textured soils for all but hydrologic soil group B, for which fine textured soils had a slightly higher average sediment loss rate than medium textured soils. Medium textured soils are the dominate soil texture class in most regions, representing 51 percent of the cropland acres included in the study.

Example of spatial variability of sediment loss

Model results showed that sediment loss can sometimes vary substantially from field to field, even within relatively small geographic areas. This variability is primarily due to local variability in soil properties, terrain characteristics, crops grown, and agricultural practices. Two specific examples of how sediment loss varies within a local area are shown in figure 11. The diversity of soil types represented in the model simulations for these two Iowa watersheds was discussed in a previous section (fig. 4). The Lower Iowa watershed has a more diverse collection of soils with more representation of hydrologic group C soils than the Floyd watershed; hydrologic group C soils have slower infiltration rates and tend to result in more surface runoff than group A or B soils. The two watersheds also have slightly different climates. The Lower Iowa watershed has higher annual precipitation (36 in/yr) than the Floyd watershed (29 in/yr). Surface water runoff for the Lower Iowa watershed averaged 5.4 inches per year, whereas surface water runoff for the Floyd watershed averaged only 3.2 inches per year.

As a result of these factors, as well as management related factors, the average annual sediment loss rate for the Lower Iowa watershed (3.7 ton/a/yr) was over twice as high as sediment loss for the Floyd watershed (1.6 ton/a/yr). Within the Lower Iowa watershed, model simulations show that sediment loss estimates varied dramatically among the soils represented, ranging from 0.1 to 17.2 tons per acre per year. Although less pronounced, significant variation among soils also occurred in the Floyd watershed, where sediment loss estimates ranged from 0.5 to 4.3 tons per acre per year for different soils.

Figure 11 also demonstrates the importance of minor soils in the assessment and treatment of soil erosion problems. Each watershed had three dominant soils that accounted for 10 percent or more of the cropland acreage, indicated by the red bars in figure 11. However, the highest sediment loss estimates in both watersheds were associated with the minor soils. In the Lower Iowa watershed, the seven soils with the highest sediment loss estimates—all greater than 7 tons per acre—accounted for 34 percent of the total sediment loss for the watershed, but only represented 12 percent of the cropland acres. In the Floyd watershed, the two soils with the highest sediment loss estimates (4.3 and 3.9 ton/a) represented only 7 percent of the cropland acres but accounted for 19 percent of the total sediment loss for the watershed.

Effects of tillage practices on sediment loss

Sediment loss estimates reported in this study accounted for conservation tillage currently practiced on cropland acres (table 11). As conservation tillage practices have a direct influence on sheet and rill erosion processes, the sediment loss estimates reported here would have been much higher had these tillage effects not been taken into account. To assess the effects that conservation tillage had on sediment loss estimates, the subset of model runs where all three tillage systems—conventional tillage, mulch tillage, and no-till—were present within a URU was defined to be the domain for examining the effects of tillage (table 12 and related discussion). This tillage comparison subset of model runs included eight crops and represented about 70 percent of the cropland acres covered by the study.

For the 208 million acres in the tillage comparison subset, the tillage-effects baseline sediment loss averaged 1.7 tons per acre per year (table 24), slightly higher

Figure 10 Average per-acre sediment loss estimates (MUSLE)–by hydrologic soil group and soil texture group

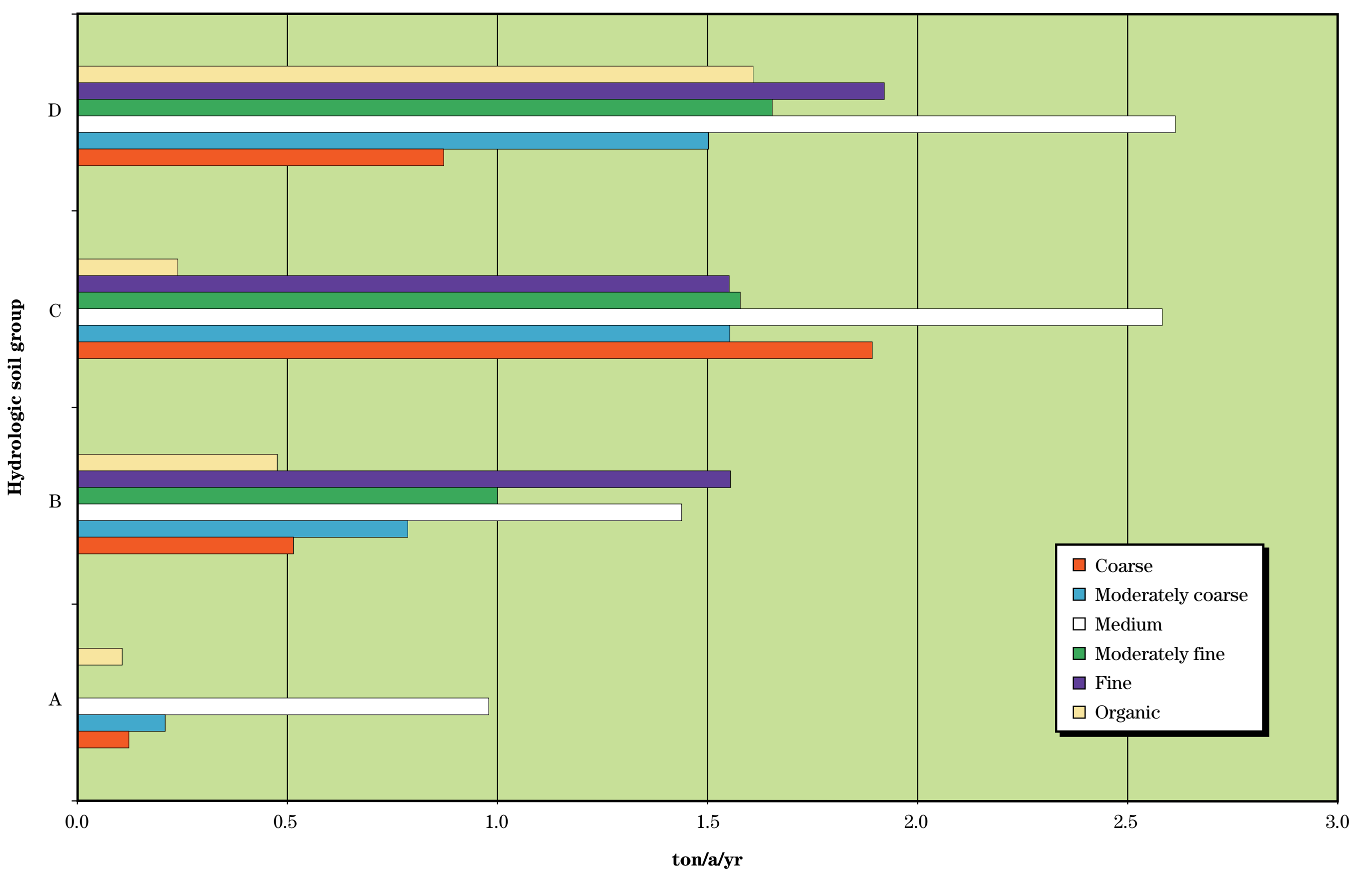
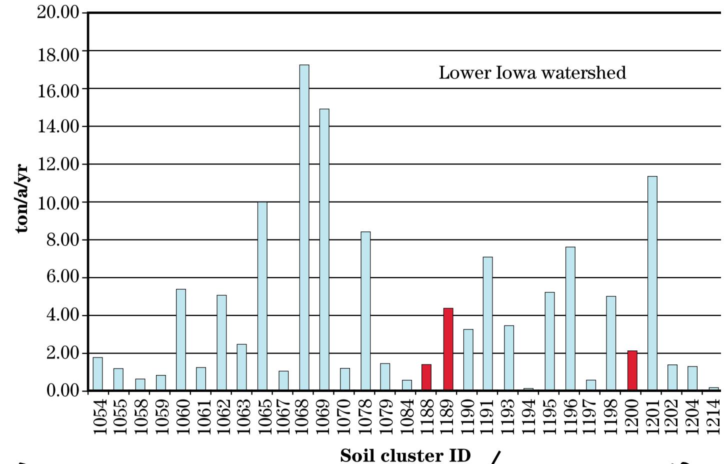
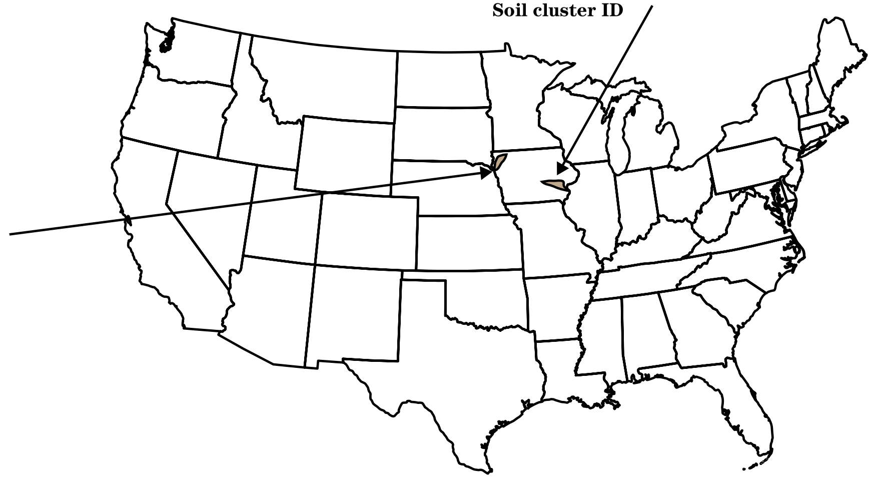


Figure 11 Variability in sediment loss estimates (MUSLE) within two IA watersheds

Soil cluster	Representative soil	Texture group	Hydrologic soil group	Soil cluster	Representative soil	Texture group	Hydrologic soil group
1054	Fairhaven	Medium	B	1189	Lagoda	Medium	B
1055	Kossuth	Moderately fine	B	1190	Sharpsburg	Moderately fine	B
1056	Alton	Moderately fine	C	1191	Adair	Medium	C
1057	Galva	Moderately fine	B	1192	Kenyon	Medium	B
1058	Hoopeston	Moderately coarse	B	1193	Marshall	Moderately fine	B
1059	Coland	Moderately fine	B	1194	Sparta	Coarse	A
1060	Tama	Medium	B	1195	Huntsville	Medium	B
1061	Coppock	Medium	B	1196	Downs	Medium	B
1062	Shelby	Moderately fine	B	1197	Village	Medium	B
1063	Turlin	Medium	B	1198	Lineville	Medium	C
1065	Fayette	Medium	B	1200	Humeston	Medium	C
1067	Nodaway	Medium	B	1201	Lamoni	Fine	C
1068	Gara	Medium	C	1202	Wabash	Moderately fine	D
1069	Lindley	Medium	C	1203	Terril	Medium	B
1070	Colo	Moderately fine	B	1204	Floyd	Medium	B
1074	Ida	Medium	B	1207	Monona	Medium	B
1078	Adair	Moderately fine	C	1209	Racine	Medium	B
1079	Lamont	Moderately coarse	B	1212	Spicer	Moderately fine	B
1084	Dickinson	Moderately coarse	B	1214	Chelsea	Coarse	A
1188	Ely	Medium	B				





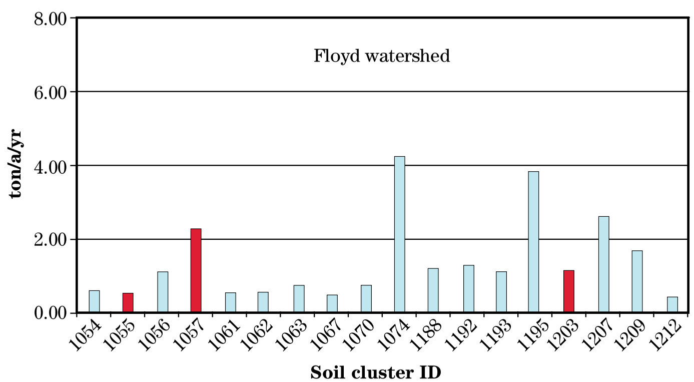


Table 24 Effects of tillage practices on estimates of sediment loss (ton/a/yr)

	Acres in tillage comparison subset (1,000s)	Sediment loss				Change relative to the tillage-effects baseline			Change relative to conventional tillage	
		Tillage-effects baseline	Conventional tillage	Mulch tillage	No-till	Conventional tillage	Mulch tillage	No-till	Mulch tillage	No-till
By region										
Northeast	6,034	5.5	7.1	5.0	1.6	1.6	-0.6	-3.9	-2.1	-5.5
Northern Great Plains	56,551	0.5	0.7	0.5	0.2	0.2	-0.1	-0.4	-0.2	-0.6
South Central	24,879	2.3	3.4	2.4	0.4	1.1	0.1	-1.9	-1.0	-3.0
Southeast	4,442	2.0	3.1	2.1	0.6	1.1	0.2	-1.4	-1.0	-2.5
Southern Great Plains	17,746	0.3	0.4	0.2	0.1	0.0	-0.1	-0.3	-0.2	-0.3
Upper Midwest	96,330	2.2	3.3	2.2	0.5	1.1	0.0	-1.7	-1.1	-2.8
West	1,661	1.8	2.1	1.3	0.8	0.3	-0.5	-1.0	-0.8	-1.3
By crop										
Barley	3,256	0.4	0.5	0.3	0.2	0.1	-0.1	-0.3	-0.2	-0.3
Corn	71,016	2.4	3.3	2.3	0.6	0.8	-0.2	-1.8	-1.0	-2.6
Corn silage	4,082	6.1	7.1	5.8	2.2	0.9	-0.3	-3.9	-1.2	-4.9
Oats	2,078	1.5	1.8	1.2	0.7	0.3	-0.4	-0.8	-0.6	-1.1
Spring wheat	18,074	0.4	0.5	0.3	0.1	0.1	-0.1	-0.3	-0.2	-0.4
Sorghum	7,697	1.1	1.3	0.9	0.2	0.3	-0.1	-0.8	-0.4	-1.1
Soybeans	62,967	1.7	3.0	2.1	0.3	1.3	0.4	-1.4	-0.9	-2.7
Winter wheat	38,473	0.7	1.0	0.5	0.2	0.3	-0.2	-0.5	-0.5	-0.8
All crops and regions	207,642	1.7	2.5	1.7	0.4	0.8	0.0	-1.3	-0.8	-2.1

Note: The subset used for this analysis includes only those URUs where all three tillage systems were present. The tillage-effects baseline results represent the mix of tillage systems as reported in the Crop Residue Management Survey for 2000 (CTIC 2001). Tillage-effects baseline results reported in this table will differ from results reported in table 22 because they represent only about 70 percent of the acres in the full database. Results presented for each tillage system represent sediment loss rates as if all acres had been modeled using a single tillage system.

than the 1.5 tons per acre per year estimate for the full set of NRI sample points included in the study. Table 12 shows the extent to which each of the three tillage systems are represented in the tillage-effects baseline. Model simulation results showed that sediment loss would have averaged nearly 2.5 tons per acre per year if conventional tillage had been used on all acres, indicating the tillage practices currently in use have reduced sediment loss by about 32 percent. Sediment losses for mulch tillage were similar to the tillage-effects baseline, suggesting that the mix of tillage systems in current use is roughly equivalent to mulch tillage being used on all acres, on average. Simulation of full implementation of no-till resulted in average sediment loss of less than 0.5 tons per acre annually, representing a decrease of 76 percent compared to the tillage-effects baseline and a decrease of 83 percent when compared to conventional tillage use on all acres.

The effects of tillage on sediment loss varied by both region and crop (table 24), depending on the extent to which the various tillage systems are currently practiced and differences among regions in soil characteristics, management activities, and climatic factors that affect sediment loss. In all comparisons, however, sediment loss estimates assuming mulch tillage on all acres were very close to sediment loss rate estimates for the tillage-effects baseline. These comparisons also indicate that full adoption of no-till on the eight crops would further reduce sediment loss by 1 to 4 tons per acre per year in all but the two Great Plains regions. The largest gains would occur in the Northeast region and for corn and corn silage acres in most regions. Model simulations further show that full adoption of no-till would result in less than 1 ton per acre per year of sediment loss in all regions except the Northeast and for all crops except corn silage.

Effects of three conservation practices on sediment loss

In addition to accounting for conservation tillage practices, sediment loss estimates accounted for the presence or absence of three conservation practices reported in the NRI database—contour farming, stripcropping, and terraces (table 13 and related discussion). For comparison to the results for the model runs that included conservation practices, an additional set of model runs were conducted after adjusting model settings to represent no practices. The difference between the no-practices scenario and the conservation-practices baseline scenario (consisting of the original model runs for NRI sample points with conservation practices) is used here to assess the extent to which conservation practices reduced the sediment loss estimates. These estimates of the effects of the three conservation practices are independent of the effects of tillage, as both scenarios retained the same tillage practices as used in development of the NNLSC database.

For the 31.7 million acres modeled with conservation practices, sediment loss estimates averaged 1.5 tons per acre per year (table 25), coincidently equal to the estimate for the full set of NRI sample points included in the study. Had conservation practices not been accounted for in the model simulations, sediment loss estimates on these acres would have averaged 3.3 tons per acre per year. These model simulations suggest, therefore, that the conservation practices reported by the NRI reduce sediment loss by about 54 percent, on average, for acres with one of more of the three practices.

Overall, the largest reduction—4.1 tons per acre per year—occurred for contour farming in combination with stripcropping. These acres had the highest sediment loss estimate for the no-practices scenario than any of the other categories—6.6 tons per acre per year. Contour farming alone reduced sediment loss estimates by 2.6 tons per acre per year for the acres included in the simulation, which had the second highest sediment loss rate for the no-practices scenario—5.5 tons per acre per year. The most prevalent practice set—contour farming and terraces—reduced sediment loss estimates from 2.8 tons per acre per year without practices to 1.0 ton per acre per year, on average. In terms of percent reductions relative to the no-practices scenario, contour farming in combination with one or more of the other two practices reduced sediment loss estimates by over 60 percent. Terraces only or stripcropping only was generally associated with acres that had lower sediment loss estimates without practices (about 2 ton/a/yr on average), and thus, resulted in sediment loss reductions of only about 1 ton per acre per year on average.

The effects of conservation practices varied considerably by region (table 25). The largest reductions occurred in regions with the highest sediment loss estimates—the Northeast and Upper Midwest regions. The percentage reductions were in the neighborhood of 50 percent for each of the regions on average, except

Table 25 Effects of three conservation practices on estimates of sediment loss (ton/a/yr)

Region	Conservation practices	Number of NRI sample points	Acres (1,000s)	Sediment loss			
				Conservation-practices base-line scenario	No-practices scenario	Difference	Percent difference relative to no-practices scenario
All regions	Contour farming only	3,728	5,965	3.0	5.5	-2.6	-46
	Contour farming and stripcropping	1,183	1,764	2.5	6.6	-4.1	-62
	Contour farming and terraces	7,883	14,728	1.0	2.8	-1.8	-66
	Contour farming, stripcropping, and terraces	31	64	0.8	2.5	-1.7	-69
	Stripcropping only	1,308	2,930	1.1	2.0	-0.8	-42
	Terraces only	3,268	6,285	1.2	1.9	-0.7	-37
	All practices	17,401	31,737	1.5	3.3	-1.8	-54
Northeast	Contour farming only	338	485	5.0	8.4	-3.4	-40
	Contour farming and stripcropping	454	595	3.4	8.2	-4.8	-58
	Stripcropping only	423	526	4.0	7.2	-3.2	-45
	All practices	1,215	1,606	4.1	7.9	-3.9	-49
Southeast	Contour farming only	275	456	2.5	4.5	-2.0	-44
	Contour farming and terraces	132	234	0.9	3.1	-2.2	-71
	Terraces only	52	92	1.4	3.0	-1.5	-52
	All practices	459	782	1.9	3.9	-2.0	-51
South Central	Contour farming only	110	172	3.8	7.7	-3.9	-51
	Contour farming and terraces	1,173	1,963	1.2	3.5	-2.4	-67
	Terraces only	1,169	1,974	1.8	2.9	-1.1	-37
	All practices	2,452	4,109	1.6	3.4	-1.8	-53
Upper Midwest	Contour farming only	2,625	4,239	3.1	5.9	-2.8	-47
	Contour farming and stripcropping	702	1,106	2.1	5.9	-3.8	-65
	Contour farming and terraces	3,621	5,293	1.9	5.3	-3.5	-65
	Stripcropping only	156	231	2.9	5.1	-2.2	-43
	Terraces only	637	985	2.5	4.0	-1.5	-38
	All practices	7,741	11,853	2.4	5.5	-3.1	-56

Table 25 Effects of three conservation practices on estimates of sediment loss (ton/a/yr)—Continued

Region	Conservation practices	Number of NRI sample points	Acres (1,000s)	Sediment loss			
				Conservation-practices base-line scenario	No-practices scenario	Difference	Percent difference relative to no-practices scenario
Northern Great Plains	Contour farming only	268	365	0.8	1.5	-0.7	-50
	Contour farming and terraces	1,370	3,553	0.3	0.6	-0.4	-58
	Stripcropping only	602	1,945	0.2	0.2	0.0	-18
	Terraces only	213	495	0.6	0.8	-0.3	-32
	All practices	2,453	6,357	0.3	0.6	-0.3	-49
Southern Great Plains	Contour farming only	104	235	0.3	0.6	-0.3	-53
	Contour farming and terraces	1,585	3,681	0.2	0.8	-0.5	-70
	Stripcropping only	80	149	0.1	0.1	0.0	-27
	Terraces only	1,122	2,677	0.4	0.7	-0.2	-35
	All practices	2,891	6,743	0.3	0.7	-0.4	-56
West	Terraces only	72	58	0.6	0.8	-0.2	-24

Note: Results for conservation practices and combinations of practices based on less than 20 NRI sample points are not shown in the regional breakdowns, but these data are included in the aggregated results for all regions.

for the West where the percentage reduction averaged 24 percent. Conservation practices in the West region, however, were represented by only 72 NRI sample points, all with terraces only, and may not be representative of conservation effects in this region because of the partial coverage of cropland acres in the study.

Assessment of critical acres for sediment loss

Acres with the highest estimates of sediment loss are identified here as critical acres. Since not all conservation practices were taken into account in the model simulations, these sediment loss estimates actually represent the potential for sediment loss. To the extent that buffers, field borders, and cover crops, for example, are present, the estimates of sediment loss reported here would be overstated and possibly some critical acres misidentified.

Some regions of the country have been shown in this study to have a much higher potential for sediment loss than other areas of the country. Moreover, as shown in map 9 and in the example for the two Iowa watersheds, sediment loss estimates often varied considerably within relatively small geographic areas. Estimates of the average sediment loss by region and by crops within regions mask much of this underlying variability. Table 26 demonstrates the extent of both regional and local variability by presenting the percentiles of sediment loss estimates for each region. The fifth and tenth percentiles (representing the per-acre sediment loss threshold below which 5 percent and 10 percent of the acres, respectively, would have lower sediment loss estimates) are all below 0.2 tons per acre per year. Similarly, results for the 25th percentile show that in every region 25 percent of the acres had sediment loss estimates less than 1 ton per acre per year. The median, or 50th percentile, is close to or below 1 ton per acre per year for all but the South Central region. Thus, even in the Northeast and the South Central regions, which had the highest average sediment loss estimates, there are a substantial number of acres with very low potential for sediment loss. As shown by the median sediment loss estimate for all regions, half of the cropland acres included in the study had sediment loss estimates less than 0.6 tons per acre per year.

The bulk of the distribution of sediment loss estimates is below the mean value in all regions, as indicated by mean values that exceed median values. The most extreme example of this is for the Northeast region, where the mean sediment loss estimate of 3.2 tons per acre per year is over three times greater than the median estimate of 0.85 tons per acre per year (table 26). For some regions, the mean value equals or approaches the 75th percentile. This condition of disproportionality exists because of a minority of sample points with very high sediment loss estimates. These sample points are defined here as critical acres, which, if adequately treated with conservation practices, are likely to have the greatest effect on offsite impacts associated with sediment loss from farm fields.

Five categories of critical acres, representing different degrees of severity, are defined on the basis of national level results:

- acres where per-acre sediment loss is above the 95th percentile (5.963 ton/a/yr) for all acres included in the study
- acres where per-acre sediment loss is above the 90th percentile (3.915 ton/a/yr) for all acres included in the study
- acres where per-acre sediment loss is above the 85th percentile (2.900 ton/a/yr) for all acres included in the study
- acres where per-acre sediment loss is above the 80th percentile (2.315 ton/a/yr) for all acres included in the study
- acres where per-acre sediment loss is above the 75th percentile (1.847 ton/a/yr) for all acres included in the study

The regional representation of critical acres is shown in table 27 for each of the five categories. Over 90 percent of the acres with per-acre sediment loss estimates in the top 5 percent were in three regions—the Upper Midwest region (46% of critical acres), the South Central region (30% of critical acres), and the Northeast region (18% of critical acres.). As the criterion for critical acres expanded from the top 5 percent to the top 25 percent, the representation of critical acres in other regions expanded somewhat, while the share of critical acres in the Northeast region fell to 7 percent. In the South Central region, half of the cropland acres were designated as critical acres in the top

Table 26 Percentiles of sediment loss estimates (ton/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	3.186	0.000	0.000	0.001	0.850	4.345	9.731	13.515
Northern Great Plains	72,396,500	36,035	0.465	<.001	0.016	0.079	0.230	0.472	0.982	1.864
South Central	45,349,900	27,465	2.769	0.002	0.156	0.900	1.849	3.378	5.941	8.725
Southeast	13,394,400	8,955	1.607	<.001	0.002	0.088	0.604	1.730	3.794	6.930
Southern Great Plains	32,096,000	14,495	0.358	0.007	0.017	0.069	0.193	0.422	0.835	1.387
Upper Midwest	112,580,900	74,691	1.945	0.000	0.019	0.481	1.117	2.464	4.634	6.792
West	9,018,400	5,644	0.548	0.000	0.000	0.016	0.103	0.359	1.511	2.044
All regions	298,478,000	178,567	1.540	<.001	0.007	0.146	0.608	1.847	3.915	5.963

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower sediment loss estimates.

Table 27 Critical acres for sediment loss

		Per-acre loss in top 5 percent nationally		Per-acre loss in top 10 percent nationally		Per-acre loss in top 15 percent nationally		Per-acre loss in top 20 percent nationally		Per-acre loss in top 25 percent nationally	
Region	Acres	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Northeast	13,641,900	2,604,900	17.5	3,749,100	12.6	4,382,600	9.8	4,890,400	8.2	5,465,700	7.3
Northern Great Plains	72,396,500	105,600	0.7	693,900	2.3	2,152,000	4.8	2,982,600	5.0	3,686,800	4.9
South Central	45,349,900	4,472,100	30.0	9,262,400	31.0	13,849,600	30.9	18,477,900	31.0	22,677,100	30.4
Southeast	13,394,400	803,800	5.4	1,281,900	4.3	2,147,100	4.8	2,739,200	4.6	3,195,400	4.3
Southern Great Plains	32,096,000	11,100	0.1	54,700	0.2	267,500	0.6	410,600	0.7	621,100	0.8
Upper Midwest	112,580,900	6,844,100	45.9	14,624,100	49.0	21,681,600	48.4	29,765,200	50.0	38,174,700	51.2
West	9,018,400	65,900	0.4	181,700	0.6	283,000	0.6	322,500	0.5	798,500	1.1
All regions	298,478,000	14,907,500	100.0	29,847,800	100.0	44,763,400	100.0	59,588,400	100.0	74,619,300	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 26. Other columns correspond to table 26 in a similar manner.

25 percent for sediment loss. In the Northeast region, 40 percent of the cropland acres were designated as critical acres in the top 25 percent for sediment loss.

These critical acres accounted for the bulk of the 459,622 thousand tons per year of sediment loss. The 95th percentile category, representing the 5 percent of acres with the highest per-acre losses, accounted for 34 percent of the total tons of sediment loss. The 25 percent of acres with the highest per-acre losses accounted for 76 percent of the total tons of sediment loss.

Percentile	Percent of total tons of sediment loss
95th	34.0
90th	49.6
85th	60.5
80th	68.9
75th	75.7

Wind erosion

Modeling wind erosion

Wind erosion occurs when the soil is unprotected and wind velocity exceeds about 13 miles per hour near the ground surface. The particles are lifted into the air and are either suspended and carried away by the wind or fall back to the surface and dislodge other soil particles. This process destroys the surface crust, creating a condition even more vulnerable to erosion. Soil grains too large to be lifted off the surface move along the surface and are deposited in areas protected from the wind. Wind strength, tillage, vegetative cover, and the texture and structure of the soil are primary determinants of wind erosion. Plant cover and crop residue greatly reduce the potential for wind erosion. The shape, size, and arrangement of aggregates are also important in wind erosion; strong bonds and large aggregates provide more resistance to erosive forces. Organic matter enhances soil structure, increases water infiltration, and thereby reduces the potential for wind erosion.

Wind erosion is estimated in EPIC using the Wind Erosion Continuous Simulation (WECS) model, which incorporates the daily distribution of wind speeds as the force driving erosion (Williams 1995). In essence, the equation estimates potential wind erosion for a smooth bare soil as a function of wind speed, soil particle size, and the ratio of soil water to water holding capacity in the top 10 millimeters (0.4 in) of the soil. Potential erosion is then adjusted downward to account for inherent soil properties, field characteristics, and management practices using four factors:

- soil erodibility
- surface roughness
- vegetative cover
- unprotected distance across the field in the wind direction

Model simulation results for wind erosion

Wind erosion, both on a per-acre basis and as total tons, was largely restricted to two regions—the Northern Great Plains and Southern Great Plains

(maps 11 and 12). These two regions accounted for 89 percent of the total tons of wind erosion estimated for cropland acres included in this study (table 28). Low wind erosion rates—usually less than 1 ton per cropland acre per year—occurred in the Upper Midwest and South Central regions, accounting for about 10 percent of the total. The Northeast, Southeast, and West regions accounted for less than 1 percent of the total wind erosion.

The most vulnerable cropland acres for wind erosion—shown in dark red and red in map 11—occur mostly in northwestern Texas, central Kansas, Northeast Colorado, and parts of Nebraska, representing about 3 percent of cropland acres included in the study. Model estimates of wind erosion rates for these acres averaged over 8 tons per acre per year. Another 3 percent of cropland acres had average wind erosion rates ranging between 3 and 8 tons per acre per year and are found in the same areas as the most vulnerable acres. About 10 percent of the cropland acres had average wind erosion rates between 1 and 3 tons per acre per year; the preponderance of these acres is also found in the Great Plains states.

Summary of wind erosion results by region and crop

Wind erosion rates in the Southern Great Plains averaged over 5 tons per acre per year and accounted for 55 percent (165 million tons per year) of the total wind erosion (table 28). The majority of this wind erosion was on cotton acres (101 million ton/yr), where the average annual wind erosion rate was 14 tons per acre per year. Wind erosion rates in this region were also high for peanuts (9.2 ton/a/yr), corn (6.2 ton/a/yr) and sorghum (5.3 ton/a/yr).

Wind erosion rates in the Northern Great Plains were much lower, averaging 1.4 tons per acre per year for cropland acres. Corn accounted for over half of the total wind erosion in this region, averaging 3.6 tons per acre per year. Wind erosion rates in this region were also high for corn silage (4.0 ton/a/yr) and sorghum (3.5 ton/a/yr).

Wind erosion rates on irrigated crops were close to the rates for non-irrigated crops for most crops in most regions (table 29). Irrigated corn acres in the Southern Great Plains region, however, had much higher wind erosion rates than non-irrigated corn acres in that region, averaging 8 tons per acre per year for irrigated corn acres and 1 ton per acre per year for non-irrigated corn acres. Corn in the Northern Great Plains region similarly had higher wind erosion rates for irrigated acres than for non-irrigated acres, differing by about 2.2 tons per acre per year. These higher rates for irrigated corn represent acreage in the more arid areas within each region where corn usually cannot be produced without irrigation.

Effects of soil properties on wind erosion

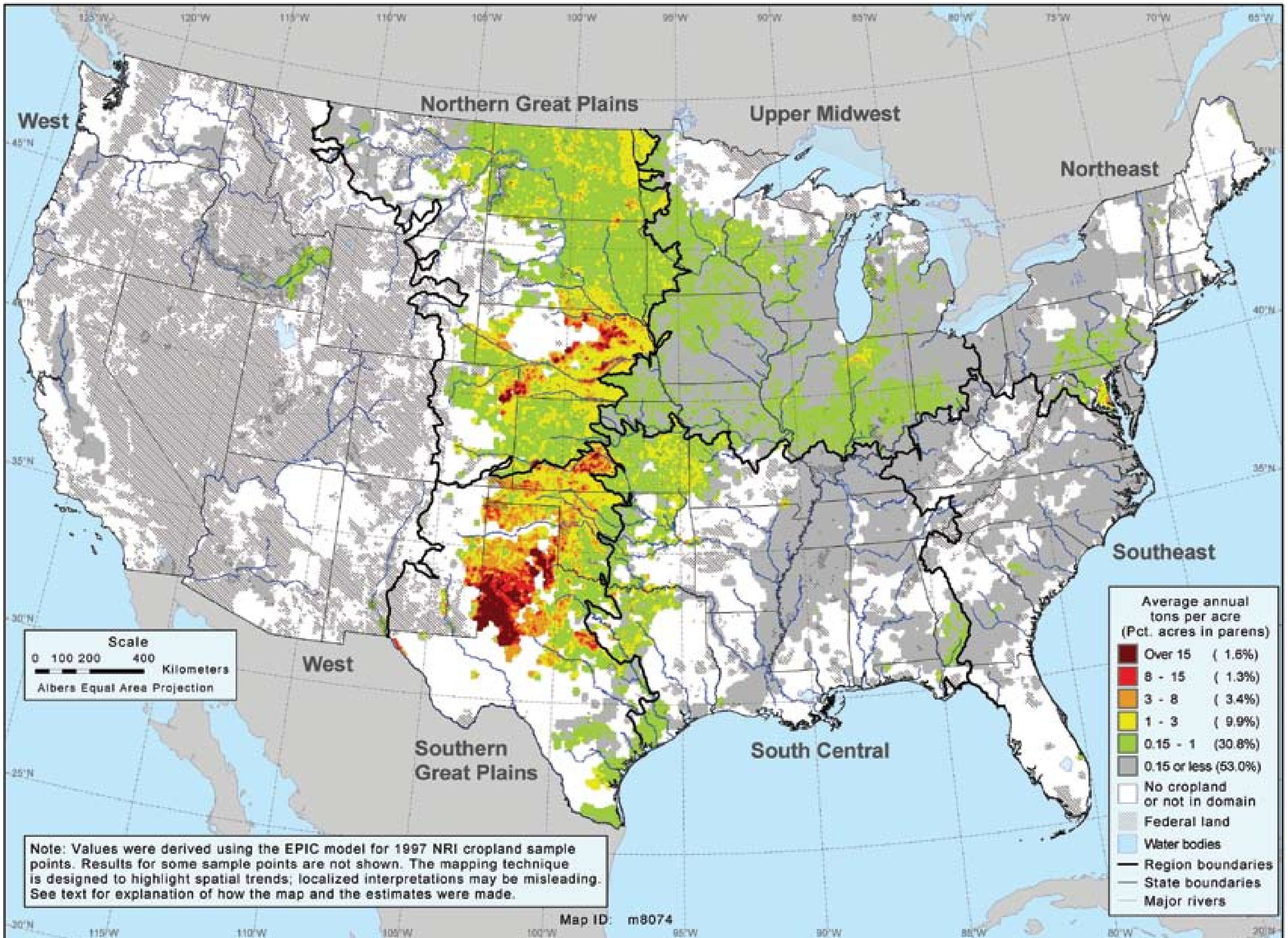
Model simulation results showed that soil texture and hydrologic soil group had a pronounced effect on wind erosion estimates (fig. 12). On average, coarse textured soils had much higher wind erosion rates than other soil texture groups, followed by moderately coarse textured soils. The highest wind erosion rate was for coarse textured soils in the hydrologic soil group A—about 7 tons per acre per year. Coarse and moderately coarse textured soils represent about 30 percent of the cropland acres in the Southern Great Plains, partly explaining the high erosion rates obtained for that region. A higher proportion of coarse and moderately coarse soils occur in the Southeast region, but climatic factors are not conducive to wind erosion in the Southeast.

Effects of tillage practices on wind erosion

These estimates of wind erosion rates include the mitigating effect of conservation tillage practices. Although the effects of tillage on wind erosion rates are significant, they are more modest than observed for sediment loss when aggregated at the regional level. To assess the effects that conservation tillage had on wind erosion estimates, the subset of model runs where all three tillage systems—conventional tillage, mulch tillage, and no-till—were present within a URU was defined to be the domain for examining the effects of tillage (table 12 and related discussion). This tillage comparison subset of model runs included eight crops—barley, corn, corn silage, oats, spring wheat, sorghum, soybeans, and winter wheat—and represented about 70 percent of the cropland acres covered by the study. Results on the effects of tillage on wind erosion estimates are shown in table 30.

For the 208 million acres in the tillage comparison subset, the tillage-effects baseline wind erosion rate averaged 0.8 tons per acre per year, slightly lower than the 1.0 tons per acre per year estimate for the full set of NRI sample points included in the study. On average, accounting for tillage effects reduced wind ero-

Map 11 Estimated average annual per-acre wind erosion rate



Map 12 Estimated average annual tons of wind erosion

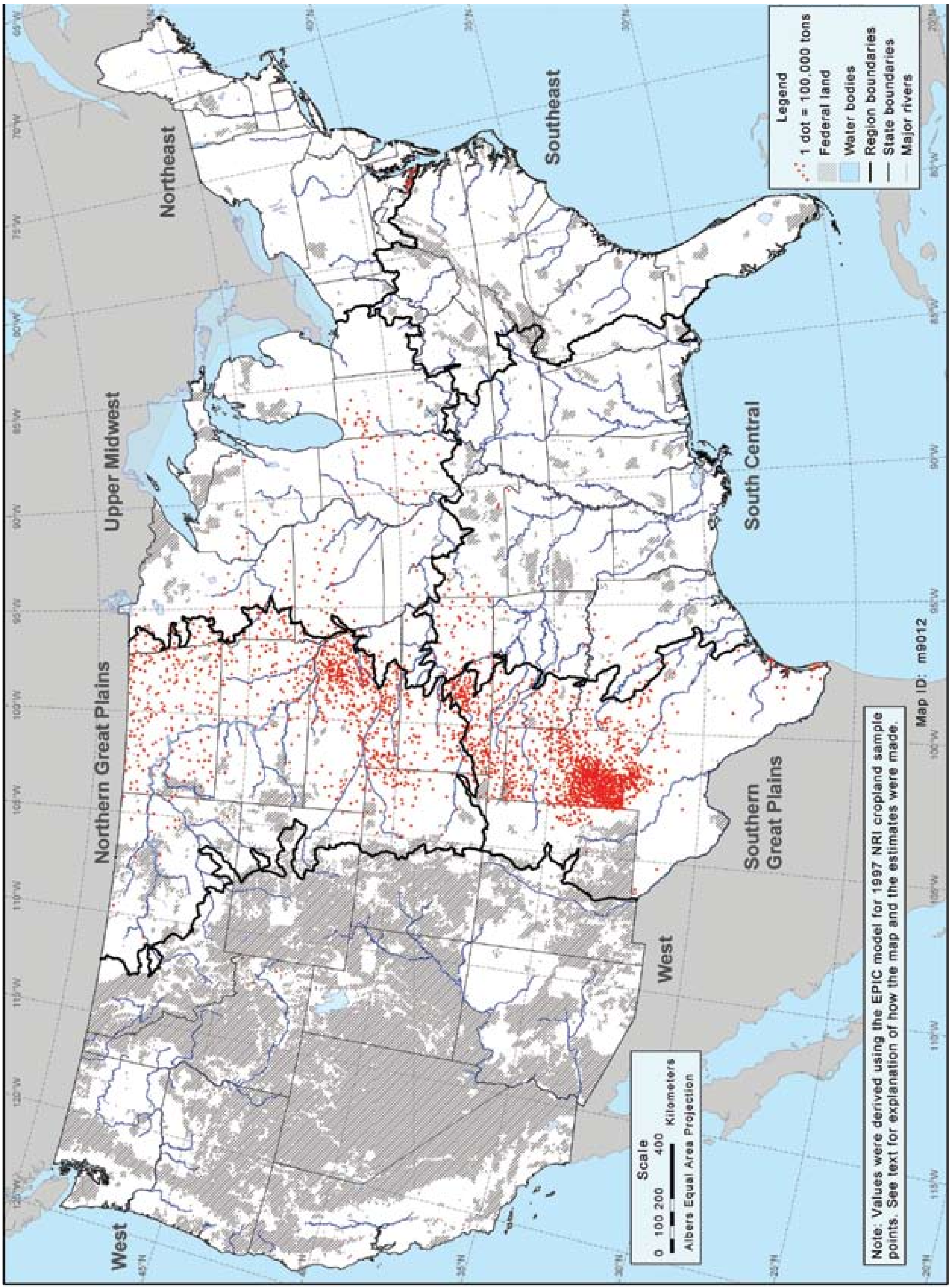


Table 28 Wind erosion rate estimates–by region and by crop within regions (average annual values)

Region	Crop	Acres (1,000s)	Tons per acre per year	Tons per year (1,000s)
By region				
Northeast	All crops	13,642	0.1	1,076
Northern Great Plains	All crops	72,397	1.4	103,286
South Central	All crops	45,350	0.3	11,511
Southeast	All crops	13,394	<0.1	201
Southern Great Plains	All crops	32,096	5.1	165,092
Upper Midwest	All crops	112,581	0.2	18,695
West	All crops	9,018	0.1	528
All regions	All crops	298,478	1.0	300,389
By crop within region*				
Northeast	Corn	2,943	0.2	454
	Corn silage	1,482	0.2	326
	Grass hay	2,369	<0.1	2
	Legume hay	4,052	0.0	0
	Oats	362	<0.1	15
	Soybeans	1,305	0.2	233
	Winter wheat	853	<0.1	15
Northern Great Plains	Barley	3,243	0.8	2,698
	Corn	15,466	3.6	55,022
	Corn silage	810	4.0	3,253
	Grass hay	2,443	<0.1	45
	Legume hay	6,152	0.0	0
	Oats	1,255	1.1	1,336
	Spring wheat	18,916	0.8	15,449
	Sorghum	1,595	3.5	5,564
	Soybeans	9,562	1.4	13,391
	Winter wheat	12,748	0.4	5,567
South Central	Corn	5,956	0.3	1,572
	Cotton	5,487	0.1	796
	Grass hay	3,347	<0.1	2
	Legume hay	1,630	0.0	0
	Peanuts	880	0.6	547
	Rice	3,004	<0.1	117
	Sorghum	2,729	1.5	4,101
	Soybeans	14,083	0.2	3,075
	Winter wheat	7,896	0.2	1,245

Table 28 Wind erosion rate estimates–by region and by crop within regions (average annual values)—Continued

Region	Crop	Acres (1,000s)	Tons per acre per year	Tons per year (1,000s)
Southeast	Corn	3,028	<0.1	44
	Corn silage	412	<0.1	4
	Cotton	2,422	<0.1	84
	Grass hay	2,000	0.0	0
	Legume hay	1,183	0.0	0
	Peanuts	479	<0.1	11
	Soybeans	2,419	<0.1	48
	Winter wheat	1,216	<0.1	1
Southern Great Plains	Corn	2,665	6.2	16,598
	Cotton	7,316	13.9	101,472
	Legume hay	677	0.0	0
	Oats	503	0.4	202
	Peanuts	484	9.2	4,455
	Sorghum	4,895	5.3	26,157
	Winter wheat	15,037	1.0	14,312
Upper Midwest	Corn	47,941	0.3	13,339
	Corn silage	1,947	0.4	784
	Grass hay	4,044	<0.1	4
	Legume hay	9,233	0.0	0
	Oats	1,388	0.2	259
	Spring wheat	815	0.2	166
	Sorghum	1,604	0.3	507
	Soybeans	40,049	0.1	3,365
	Winter wheat	5,147	<0.1	123
West	Barley	958	0.1	108
	Corn silage	297	0.1	26
	Cotton	1,631	<0.1	50
	Legume hay	1,847	0.0	0
	Potatoes	329	0.5	160
	Rice	599	0.0	0
	Spring wheat	772	0.1	104
	Winter wheat	2,118	<0.1	71

* Wind erosion rate estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Table 29 Comparison of wind erosion rates for irrigated crops to rates for non-irrigated crops (average annual values)

		Non-irrigated crops		Irrigated crops	
Region	Crop*	Acres (1,000s)	Tons per acre per year	Acres (1,000s)	Tons per acre per year
Northern Great Plains	Corn	8,785	2.6	6,680	4.8
	Legume hay	4,816	0.0	1,336	0.0
	Soybeans	8,578	1.3	984	2.2
	Winter wheat	12,086	0.4	662	0.4
South Central	Corn	5,285	0.2	671	0.4
	Cotton	3,983	0.2	1,505	0.1
	Rice	0	NA	3,004	<0.1
	Soybeans	10,498	0.3	3,585	0.1
	Winter wheat	7,341	0.2	554	0.1
Southeast	Cotton	2,115	<0.1	307	<0.1
Southern Great Plains	Corn	672	1.0	1,993	8.0
	Cotton	4,486	13.8	2,831	14.0
	Legume hay	263	0.0	414	0.0
	Peanuts	159	8.3	325	9.7
	Sorghum	3,748	5.6	1,147	4.3
	Winter wheat	13,046	1.0	1,991	0.8
Upper Midwest	Corn	46,424	0.3	1,517	0.4
	Soybeans	39,409	0.1	641	0.1
West	Barley	357	0.1	601	0.1
	Corn silage	0	NA	297	0.1
	Cotton	0	NA	1,631	<0.1
	Legume hay	159	0.0	1,688	0.0
	Potatoes	0	NA	329	0.5
	Rice	0	NA	599	0.0
	Spring wheat	197	0.1	575	0.2
	Winter wheat	1,066	<0.1	1,052	0.1

* Irrigated crops with more than 250,000 acres in a region are included in the table. These 26 crop-region combinations represent 92 percent of the irrigated acres included in the study.
NA = not applicable.

Figure 12 Average per-acre wind erosion rates–by hydrologic soil group and soil texture group

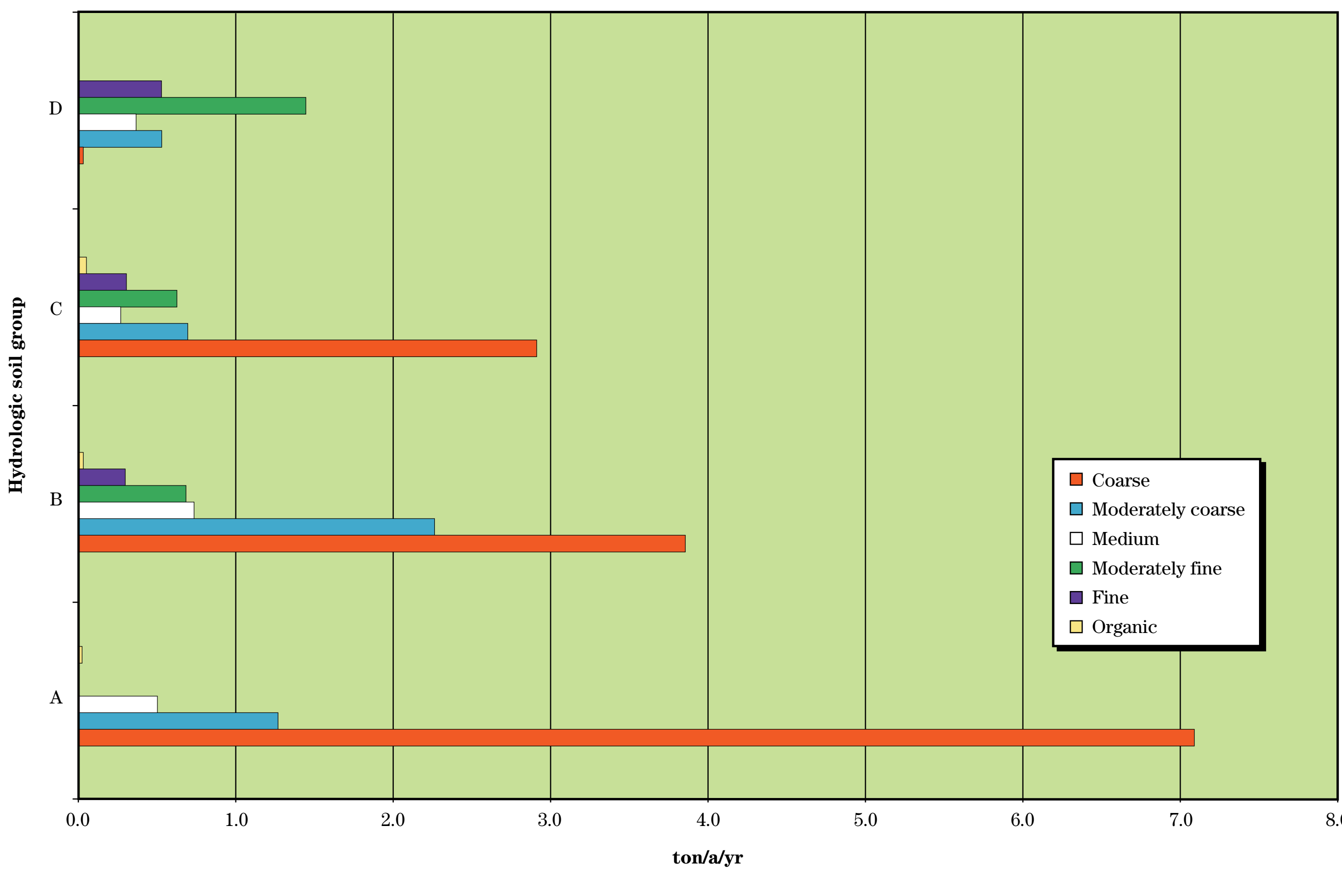


Table 30 Effects of tillage practices on estimates of wind erosion rates (ton/a/yr)

	Acres in tillage comparison subset (1,000s)	Wind erosion rate				Change relative to the tillage-effects baseline			Change relative to conventional tillage	
		Tillage-effects baseline	Conventional tillage	Mulch tillage	No-till	Conventional tillage	Mulch tillage	No-till	Mulch tillage	No-till
By region										
Northeast	6,034	0.15	0.21	0.12	0.03	0.06	-0.03	-0.12	-0.09	-0.18
Northern Great Plains	56,551	1.57	2.15	1.07	0.39	0.58	-0.50	-1.18	-1.08	-1.76
South Central	24,879	0.33	0.41	0.21	0.05	0.08	-0.12	-0.28	-0.20	-0.36
Southeast	4,442	0.01	0.01	0.01	0.00	0.00	0.00	-0.01	0.00	-0.01
Southern Great Plains	17,746	2.52	3.11	1.63	0.61	0.59	-0.89	-1.91	-1.48	-2.50
Upper Midwest	96,330	0.19	0.28	0.14	0.04	0.09	-0.05	-0.15	-0.14	-0.24
West	1,661	0.07	0.12	0.02	0.01	0.05	-0.05	-0.06	-0.10	-0.11
All regions	207,642	0.77	1.04	0.53	0.18	0.27	-0.24	-0.59	-0.51	-0.86

Note: The subset used for this analysis includes only those URUs where all three tillage systems were present. The tillage-effects baseline results represent the mix of tillage systems as reported in the Crop Residue Management Survey for 2000 (CTIC 2001). Tillage-effects baseline results reported in this table will differ from results reported in table 28 because they represent only about 70 percent of the acres in the full database Results presented for each tillage system represent wind erosion rates as if all acres had been modeled using a single tillage system.

sion rates overall by about 0.3 tons per acre per year compared to conventional tillage use on all acres, representing a reduction of 26 percent. The mitigating effect of tillage on wind erosion estimates occurred in all regions, although differences were small in regions with low wind erosion rates (table 30). In the Northern Great Plains and Southern Great Plains regions, where wind erosion rates are highest, accounting for tillage reduced wind erosion rates by about 0.6 tons per acre per year, on average, compared to conventional tillage use on all acres. This indicates that, had these tillage practices not been adopted, wind erosion rates would have been about 37 percent higher in the Northern Great Plains and 23 percent higher in the Southern Great Plains. Full adoption of mulch tillage in these two regions would further reduce wind erosion by 0.5 to 0.9 tons per acre per year. These model simulations further show that full adoption of no-till would reduce wind erosion rates by 1 to 2 tons per acre per year in the two Great Plains regions, on average, and bring the wind erosion rate to well below 1 ton per acre per year in all regions. These estimates of the effects of tillage may be understated in the Southern Great Plains region because the two crops with the highest wind erosion rates—cotton and peanuts—were not included in the analysis.

Assessment of critical acres for wind erosion

Acres with the highest wind erosion rates are identified here as critical acres. Erosion rate estimates reported in this study actually represent the potential for wind erosion as a source of soil loss from farm fields. Tillage practices were included in the assessment, but other conservation practices that are often used to help control wind erosion were not taken into account, such as windbreaks, buffers, field borders, cover crops, and stripcropping. Stripcropping was taken into account for sediment loss estimates by adjusting the P-factor, but this has no effect on wind erosion estimates in EPIC. To the extent that these practices are present, the potential for high wind erosion rates reported here would be overstated and possibly some critical acres misidentified.

Two regions of the country have been shown to have high wind erosion rates—the Southern Great Plains and Northern Great Plains regions. Even in those regions, however, high wind erosion rates were limited to a minority of the acres present. Table 31 demonstrates the extent of both regional and local variability by presenting the percentiles of wind erosion estimates for each region. Three-fourths of the cropland acres included in the study had wind erosion rates less than 0.6 tons per acre per year. For each region, the 75th percentile was nearly the same as the regional average wind erosion rate. Thus, there is a high degree of disproportionality in the wind erosion results, even in the Southern Great Plains and Northern Great Plains regions. A relatively small minority of sample points with very high wind erosion rates dominate the sample. These sample points are defined here as critical acres for wind erosion.

Five categories of critical acres, representing different degrees of severity, are defined on the basis of national level results:

- acres where per-acre wind erosion rates are above the 98th percentile (11.788 ton/a/yr) for all acres included in the study
- acres where per-acre wind erosion rates are above the 96th percentile (5.155 ton/a/yr) for all acres included in the study
- acres where per-acre wind erosion rates are above the 94th percentile (3.267 ton/a/yr) for all acres included in the study
- acres where per-acre wind erosion rates are above the 92nd percentile (2.489 ton/a/yr) for all acres included in the study
- acres where per-acre wind erosion rates are above the 90th percentile (1.983 ton/a/yr) for all acres included in the study

Higher thresholds are used to identify critical acres associated with wind erosion than are used to identify thresholds for critical acres associated with sediment loss and nutrient loss because the high wind erosion rates are limited to a much smaller subset of the cropland acres. Instead of the 95th percentile used for sediment loss, the 98th percentile is used for wind erosion, for example.

The regional representation of critical acres for wind erosion is shown in table 32 for each of the five categories. Most (86%) of the acres with per-acre wind erosion rates in the top 2 percent were in the Southern Great Plains, with the remainder in the Northern Great

Table 31 Percentiles of wind erosion estimates (ton/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	0.079	0.000	0.000	0.000	0.001	0.041	0.256	0.422
Northern Great Plains	72,396,500	36,035	1.427	0.000	0.000	0.308	0.713	1.476	2.866	3.981
South Central	45,349,900	27,465	0.254	0.000	<.001	0.002	0.013	0.122	1.132	1.607
Southeast	13,394,400	8,955	0.015	0.000	0.000	0.000	0.001	0.015	0.038	0.060
Southern Great Plains	32,096,000	14,495	5.144	0.033	0.162	0.313	1.150	6.594	16.510	22.251
Upper Midwest	112,580,900	74,691	0.166	0.000	0.000	0.030	0.094	0.213	0.333	0.424
West	9,018,400	5,644	0.059	0.000	0.000	0.000	<.001	0.004	0.151	0.311
All regions	298,478,000	178,567	1.006	0.000	0.000	0.010	0.129	0.553	1.983	4.164

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower wind erosion rates.

Table 32 Critical acres for wind erosion

		Per-acre wind erosion rate in top 2 percent nationally		Per-acre wind erosion rate in top 4 percent nationally		Per-acre wind erosion rate in top 6 percent nationally		Per-acre wind erosion rate in top 8 percent nationally		Per-acre wind erosion rate in top 10 percent nationally	
Region	**Acres**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**
Northeast	13,641,900	0	0.0	10,800	0.1	27,800	0.2	38,300	0.2	57,500	0.2
Northern Great Plains	72,396,500	812,000	13.6	2,288,200	19.2	5,299,100	29.6	9,801,100	41.0	14,135,800	47.4
South Central	45,349,900	25,900	0.4	138,200	1.2	284,300	1.6	478,500	2.0	1,265,100	4.2
Southeast	13,394,400	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Southern Great Plains	32,096,000	5,132,400	86.0	9,444,000	79.1	11,951,700	66.7	13,128,900	55.0	13,715,900	46.0
Upper Midwest	112,580,900	0	0.0	53,600	0.4	346,800	1.9	426,000	1.8	635,800	2.1
West	9,018,400	0	0.0	0	0.0	1,900	0.0	4,000	0.0	6,700	0.0
All regions	298,478,000	5,970,300	100.0	11,934,800	100.0	17,911,600	100.0	23,876,800	100.0	29,816,800	100.0

Note: The top 10 percent corresponds to the 90th percentile in table 31.

Plains. As the criterion for critical acres expands from the top 2 percent to the top 10 percent, the representation of critical acres in the Northern Great Plains expands to match that for the Southern Great Plains. In the top 10 percent category, the Northern Great Plains and the Southern Great Plains regions each had about 46 to 47 percent of the critical acres, with most of the remainder in the South Central region.

These critical acres accounted for the bulk of the 300,389 thousand tons per year of wind erosion. The 98th percentile category, representing the 2 percent of acres with the highest per-acre losses, accounted for 42 percent of the total tons of wind erosion. The 10 percent of acres with the highest per-acre losses accounted for 76 percent of the total tons of wind erosion.

Percentile	Percent of total tons of wind erosion
98th	42.3
96th	57.9
94th	66.2
92nd	71.8
90th	76.2

Nitrogen loss

Modeling the nitrogen cycle

Nitrogen is a necessary input for crop growth and production. Along with carbon and phosphorus, nitrogen provides the organic building blocks for plant growth and crop yield. Although the atmosphere is 78 percent nitrogen gas, it cannot be directly used by plants. Nitrogen molecules in the air are inert, mainly existing as two nitrogen atoms strongly bonded together (di-nitrogen gas). To be used by plants, the di-nitrogen molecules must be split apart and converted into ammonium or nitrate compounds that plants can take up and metabolize—a process called nitrogen fixation. Most nitrogen fixation is the product of biochemical processes performed by soil microorganisms. A small amount of nitrogen is converted by lightning and ultraviolet rays. Plant available nitrogen is usually in short supply under natural conditions, limiting plant growth and biomass production.

Most soil nitrogen is bound up in soil organic matter, which is partially decomposed plant and animal residue. As soil microbes consume the organic matter, ammonium or nitrate nitrogen is released, allowing the nitrogen to be recycled as plant uptake. Decomposition of organic matter, or mineralization, is typically a slow process that may take from several months to hundreds or even thousands of years, depending on the type of organic material. Intensive tillage of cropland and the introduction of oxygen into the soil increases mineralization and speeds the release of plant available nitrogen from organic sources in the soil.

Modern farming practices include the application of commercial fertilizers and manure to promote plant growth and increase crop yields. Commercial fertilizers, which are produced through chemical industrial processes, and manure applications are the primary sources of nitrogen applied. Planting soybeans, peas, and other legume crops that host symbiotic nitrogen-fixing bacteria are also an important source of plant-available nitrogen. Another source of nitrogen is atmospheric deposition. Ammonia and nitrogen oxide gasses are released into the atmosphere as a by-product from modern industrial societies (for instance, automobile emissions), from livestock and livestock production facilities, and from volatilization and denitrification of applied fertilizers, decomposing organic matter, and other soil nitrogen. These nitrogen compounds may drift with the wind and be re-deposited on cropland with rainfall or as dry deposition.

Some forms of nitrogen fertilizer, such as anhydrous ammonia, and most livestock manures contain a high percentage of ammonium nitrogen, which is highly volatile. To prevent significant loss of this nitrogen at the time of application, ammonium forms of commercial fertilizer and manures are incorporated or injected into the soil. Rainfall or application of irrigation water soon after application of manure or ammonia fertilizers will also reduce loss of ammonia. Nitrate nitrogen fertilizers are generally not volatile, but can lead to nitrogen loss to the atmosphere through denitrification processes if applied to fields where the soil moisture content is near saturation. Chemical products can be added to nitrogen fertilizers and manures to reduce the release of gaseous nitrogen.

The nitrogen cycle as simulated by EPIC consists of mineral and organic fractions (fig. 13). Organic nitrogen is partitioned into fresh, stable, and active pools, while mineral nitrogen is partitioned into ammonium or nitrate pools. The model tracks nitrogen transformations between pools within each fraction and also between the organic and mineral fractions on a daily time-step through a series of coupled equations that are solved within a mass balance framework. These equations are closely tied to other model components including the hydrology component, which controls most of the transport processes, and the plant growth component, which handles plant uptake. EPIC mineralization and immobilization transformations are based upon the PAPRAN (Seligman and Van Keulen 1981) model. Plant uptake of nitrogen is estimated using a supply and demand approach, which balances available nitrogen with an ideal nitrogen concentration in the plant for a given day.

Nitrogen inputs in EPIC simulations include nitrogen applied as ammonia, nitrate, and organic (manure) fertilizers, symbiotic bio-fixation associated with legume crops, and soluble nitrogen deposited with rainfall. Commercial nitrogen fertilizer data used in EPIC model simulations were derived from farmer surveys, as described in a previous section of this report. Manure nitrogen applications used in EPIC model simulations were derived from data on livestock populations, also

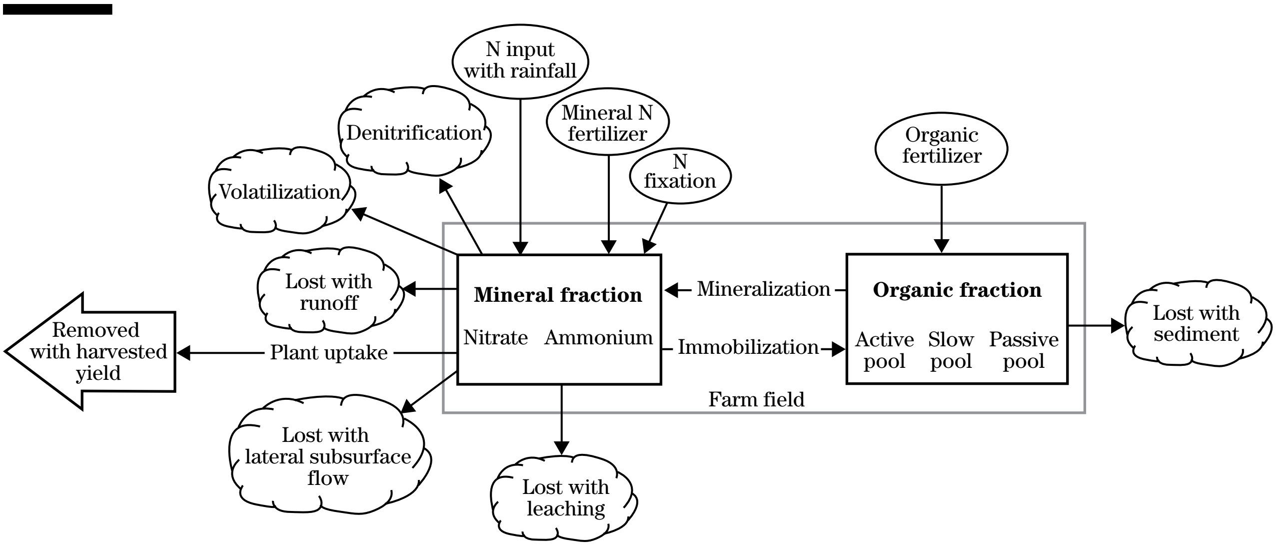
described in a previous section of this report. Daily nitrogen fixation from legumes is estimated as a fraction of daily plant uptake. Daily plant uptake is modeled as a function of soil nitrate concentration, soil-water content, and plant growth stage. The growth stage factor inhibits nitrogen fixation in young plants prior to development of functional nodules and in old plants with senescent nodules. For rainfall depositions, the rainfall concentration of soluble nitrogen was set at 0.8 parts per million. Thus, for each inch of rainfall, 0.181 pounds per acre of nitrogen was added to the system in the form of nitrate. Dry deposition and lightning fixation inputs were not included in the simulations.

EPIC simulates nitrogen exports from the field in two forms: crop removal and losses to the air and water. Nitrogen contained in the plant material is partitioned between that which is removed from the field with the harvested crop yield and that portion remaining in the residue which is added into the organic pools. Nitrogen losses include nitrates dissolved in surface runoff, percolation (leachate), and lateral subsurface flow; organic nitrogen attached to wind and waterborne sediment; and ammonia and nitrogen oxides lost to the atmosphere.

Nitrate losses in surface water runoff, lateral subsurface flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the soil layer. Organic nitrogen transport with sediment is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events. The loading function estimates the daily organic nitrogen runoff loss based on the concentration of organic nitrogen in the top soil layer, sediment yield, and nutrient enrichment ratio. The enrichment ratio is the concentration of organic nitrogen in sediment divided by that in soil. Volatilization is estimated simultaneously with the conversion of ammonia-nitrogen to nitrate-nitrogen in the nitrification process. Partitioning is regulated by a function of temperature, soil-water content, and soil pH for nitrification, while below surface volatilization is controlled by depth of ammonia within the soil, cation exchange capacity of the soil, and soil temperature. Volatilization of surface-applied ammonia is estimated as a function of temperature and wind speed.

Denitrification is an anaerobic microbial process, occurring under saturated soil moisture conditions,

Figure 13 Nitrogen cycle as modeled in EPIC



that reduces nitrates to nitrogen oxides and di-nitrogen gas molecules that are lost to the atmosphere. Denitrification rates can range from 5 to 20 percent of applied nitrogen. In EPIC, denitrification rates are regulated by a function of temperature and soil-water content that is parameterized as the fraction of field capacity soil water storage. This threshold was set at 1.01 for all model simulations conducted in this study, which resulted in no denitrification. As discussed in a previous section, the minimum depth of the water table was also set to 2 meters year-round for all model runs to simulate adequate drainage. While the assumption of adequate drainage during the crop production time period is generally desirable, the model simulations reported in this study did not account for high water tables and denitrification during times of the year when drainage is not critical for crop production (after harvest and during winter months), which is when saturated soil conditions and denitrification most often occur on cropland acres. By not accounting for poor drainage and denitrification outside of the growing season, model estimates of nitrates in leachate may be overstated in some cases, nitrates in surface water runoff may be understated in some cases, and nitrogen volatilization estimates may be understated in some cases. Total nitrogen loss, however, is generally not affected by these modeling assumptions. (In this study, nitrogen volatilization includes both gaseous nitrogen lost as ammonia, usually at the time of nitrogen application, and di-nitrogen and nitrous oxide gases generated through denitrification processes, which take place over longer periods of time.)

For comparisons of nitrogen loss to nitrogen inputs in this report, nitrogen inputs included commercial fertilizer, manure applications, bio-fixation, and atmospheric deposition. Nitrogen input from mineralization of soil organic matter is not reported or included in these comparisons, but did contribute to the pool of mineral nitrogen in the EPIC model and, therefore, is reflected in nitrogen loss estimates. In addition, it is recognized that the organic portion of manure nitrogen is not immediately available to the plant, and that the portion of manure nitrogen that is not available for plant growth in the year of application is available in subsequent years. As simulated by EPIC, manure nitrogen inputs in a given year are equal to the mineral form of nitrogen (mostly as ammonia) in the manure applied during the current year and mineralized nitrogen from the organic fraction of manure applications in previous years.

EPIC also calculates a complete daily mass balance of nitrogen, including mineralization and immobilization between the organic and mineral fractions, transformations between the pools within each fraction, and residue additions. These model outputs were not tracked or reported in this study.

Model simulation results for nitrogen inputs

Nitrogen inputs from commercial fertilizer applications, manure applications, bio-fixation, and atmospheric deposition totaled about 21 million tons per year for the 298 million acres of cropland represented by the model simulations (table 33). Of this, 49 percent (10.4 million tons) came from symbiotic bacterial-legume fixation (bio-fixation), 41 percent (8.7 million tons) was added as commercial fertilizer, 5 percent (1.1 million tons) was added as manure, and 4 percent (0.8 million tons) was added with rainfall. Soybeans, corn, and legume hay had the largest inputs with 6.3, 5.2, and 5.0 million tons per year, respectively (table 33). About half of total commercial nitrogen fertilizer and about half of the total manure nitrogen was applied to corn. The preponderance of the nitrogen inputs for the three legume crops—soybeans, peanuts, and alfalfa hay—came from bio-fixation, with relatively small amounts coming from other sources. Atmospheric deposition of nitrogen was treated in the model as a fixed concentration, but varied in importance from region to region because of differences in the amount of rainfall and cropland acres. Nitrogen from these four sources, together with soil organic nitrogen converted each year from organic to mineral form, was available for plant growth in the EPIC model simulations, where they were either taken up by the crop and removed from the field at harvest, stored in the soil, or transported from the field by wind and water.

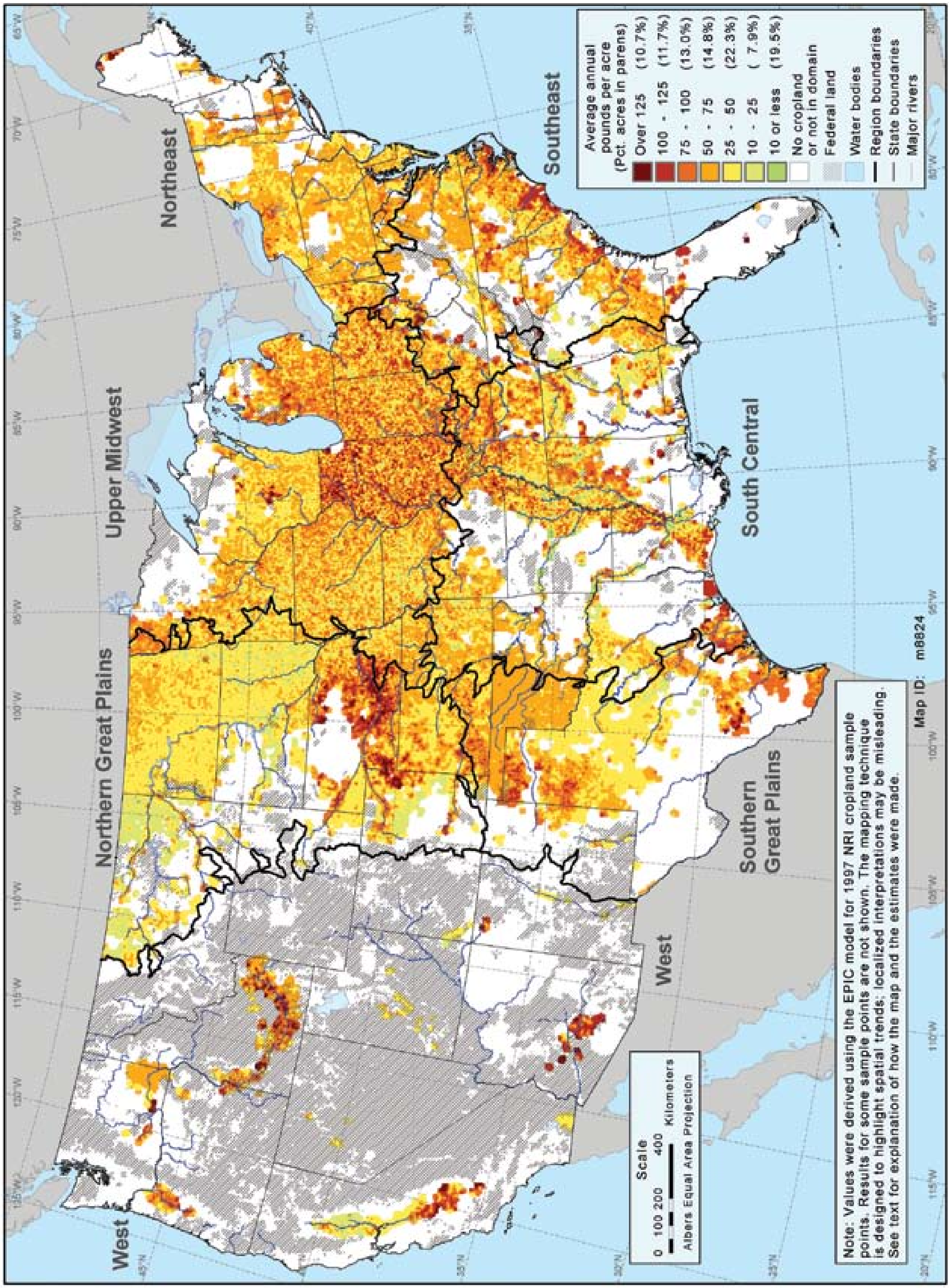
Spatial trends in nitrogen application rates

Map 13 shows the spatial distribution of average commercial fertilizer application rates that are based on the inputs used for the EPIC model simulations. Commercial fertilizer application rates varied substantially throughout most of the cropland acres, reflecting the crop mix and the associated differences in application rates by crop. The color pattern in corn and soybean production areas, for example, mainly represents the mix of corn acres receiving substantial commercial

Table 33 Sources of nitrogen inputs–by region and by crop (average annual values)

	Acres		Commercial fertilizer		Manure		Atmospheric deposition		Bio-fixation		Sum of inputs	
	1,000s	**Percent**	**Tons**	**Percent**	**Tons**	**Percent**	**Tons**	**Percent**	**Tons**	**Percent**	**Tons**	**Percent**
By region												
Northeast	13,642	4.6	388,665	4.5	146,867	13.6	48,523	5.8	1,081,687	10.4	1,665,742	7.9
Northern Great Plains	72,397	24.3	1,815,130	20.9	154,986	14.3	122,474	14.6	907,910	8.7	3,000,645	14.3
South Central	45,350	15.2	1,290,546	14.8	85,795	7.9	197,007	23.4	1,993,185	19.2	3,566,628	17.0
Southeast	13,394	4.5	423,992	4.9	82,103	7.6	55,854	6.6	468,580	4.5	1,030,529	4.9
Southern Great Plains	32,096	10.8	952,920	11.0	74,517	6.9	61,552	7.3	106,041	1.0	1,195,054	5.7
Upper Midwest	112,581	37.7	3,504,461	40.3	466,355	43.1	344,878	41.0	5,579,239	53.6	9,894,962	47.1
West	9,018	3.0	318,839	3.7	71,619	6.6	10,313	1.2	263,443	2.5	664,220	3.2
All regions	298,478	100.0	8,694,553	100.0	1,082,242	100.0	840,601	100.0	10,400,085	100.0	21,017,780	100.0
By crop												
Barley	4,635	1.6	171,683	2.0	2,244	0.2	7,313	0.9	0	0.0	181,242	0.9
Corn	78,219	26.2	4,369,865	50.3	552,495	51.1	231,507	27.5	0	0.0	5,153,867	24.5
Corn silage	5,197	1.7	186,760	2.1	298,616	27.6	14,971	1.8	0	0.0	500,345	2.4
Cotton	16,858	5.6	560,237	6.4	12,369	1.1	51,108	6.1	0	0.0	623,746	3.0
Grass hay	14,596	4.9	445,865	5.1	87,698	8.1	47,426	5.6	0	0.0	580,989	2.8
Legume hay	24,776	8.3	444,358	5.1	18,299	1.7	65,268	7.8	4,512,759	43.4	5,040,690	24.0
Oats	3,772	1.3	43,934	0.5	852	0.1	9,303	1.1	0	0.0	54,096	0.3
Peanuts	1,843	0.6	17,372	0.2	1,629	0.2	7,207	0.9	63,490	0.6	89,699	0.4
Potatoes	987	0.3	72,952	0.8	1,315	0.1	2,268	0.3	0	0.0	76,535	0.4
Rice	3,637	1.2	190,001	2.2	7	<0.1	15,522	1.8	0	0.0	205,541	1.0
Spring wheat	20,503	6.9	423,081	4.9	4,206	0.4	32,545	3.9	0	0.0	459,961	2.2
Sorghum	10,897	3.7	444,695	5.1	16,465	1.5	27,978	3.3	0	0.0	489,144	2.3
Soybeans	67,543	22.6	143,954	1.7	59,224	5.5	221,487	26.3	5,823,836	56.0	6,248,524	29.7
Winter wheat	45,014	15.1	1,179,798	13.6	26,822	2.5	106,697	12.7	0	0.0	1,313,400	6.2
All crops	298,478	100.0	8,694,553	100.0	1,082,242	100.0	840,601	100.0	10,400,085	100.0	21,017,780	100.0

Map 13 Average annual commercial fertilizer application rates for nitrogen in model simulations



fertilizer interspersed among soybean acres receiving little to moderate commercial fertilizer. In some places, the application rates show sharp differences between neighboring states, revealing the state-level nature of the available farmer survey information.

Map 14 shows the spatial distribution of manure applications used for the model simulations. Class breaks used in map 14 were the same as used for map 13 to facilitate comparisons between manure and commercial fertilizer sources of nitrogen. The broad areas of intensive animal agriculture can be identified in map 14 by the higher application rates: swine production in Iowa and North Carolina; poultry production in the Mid-Atlantic area and parts of the Southeast; dairy production in the Northeast, in Minnesota, Wisconsin, and parts of Michigan, and in areas in California and parts of Texas; and fattened cattle production in the mid-Great Plains area and areas throughout the West. These hot spots for manure application correspond closely to areas of intensive livestock production reported by Kellogg et al. (2000).

The percentage of acres shown in the legend of map 14 for each application rate class is the percentage of NRI acres for which some portion of the acres at an NRI point received manure, not the percentage of acres treated with manure. In areas of intensive livestock production, the portion of acres at the NRI point receiving manure could be high, but in most other areas, it was low, often below 10 percent. Overall, only 3.6 percent of the acres included in the study received manure applications (table 19) in the model simulations. Also evident in map 14 are broad areas of cropland that received almost no manure applications.

The per-acre application rates for nitrogen from manure and nitrogen from commercial fertilizer presented in maps 13 and 14 (as well as application rates shown in tables) are the averages for all cropland acres, including acres without manure application or without commercial fertilizer application. The averages shown are thus lower than the application rates assigned to each crop as model inputs, such as those shown in tables 15 and 18. For example, the manure nitrogen application rates for corn in climate cluster 1 in Nebraska ranged from 146 to 342 pounds of nitrogen per acre for cropland acres associated with manure producing farms and ranged from 79 to 184 pounds of nitrogen per acre for cropland acres associated with manure receiving farms, depending on the yield class (table 18). However, only 5.3 percent of the total corn acres received manure in that state-climate cluster. The overall average manure nitrogen application rate for corn in the Nebraska portion of climate cluster 1 was about 10 pounds per acre, which is the value represented in map 14.

An important feature shown on both maps 13 and 14 is the variability in average nitrogen applications even within fairly localized areas.

Nitrogen input estimates by region

Northeast region. The highest per-acre nitrogen input was in the Northeast region (fig. 14, table 34), averaging 244 pounds of nitrogen per acre of cropland. About 65 percent of nitrogen inputs in this region were from bio-fixation (fig. 15), followed by 23 percent for commercial fertilizer, 9 percent for manure, and 3 percent for atmospheric deposition. The average rate for manure application was also highest in the Northeast (fig. 14), averaging 22 pounds of nitrogen per acre of cropland. This was largely due to 1.5 million acres of corn silage, which represented a third of the acreage of non-legume row crops in the Northeast and had an average application rate of 114 pounds of manure nitrogen per acre.

Upper Midwest region. The Upper Midwest region had the second-highest per acre nitrogen input, averaging 176 pounds per cropland acre (table 34). Nitrogen inputs in the Upper Midwest were disproportionately high, representing nearly half of the total nitrogen inputs for all regions but accounting for only 38 percent of the cropland acres (table 33). About 56 percent of the nitrogen inputs in this region was bio-fixation, 35 percent was commercial fertilizer, 5 percent was manure, and 4 percent was atmospheric deposition (fig. 15).

South Central and Southeast regions. Nitrogen inputs in the South Central region and the Southeast averaged 157 and 154 pounds per acre of cropland, respectively (fig. 14). The percent representation by source was similar to that in the Upper Midwest region, although, both regions received more nitrogen from atmospheric deposition and the Southeast received slightly more nitrogen from manure applications on a per-acre basis. Among all the regions, atmospheric deposition of nitrogen was highest in these two regions—averaging 8 to 9 pounds per acre—because of higher precipitation.

Map 14 Average annual manure nitrogen application rates in model simulations

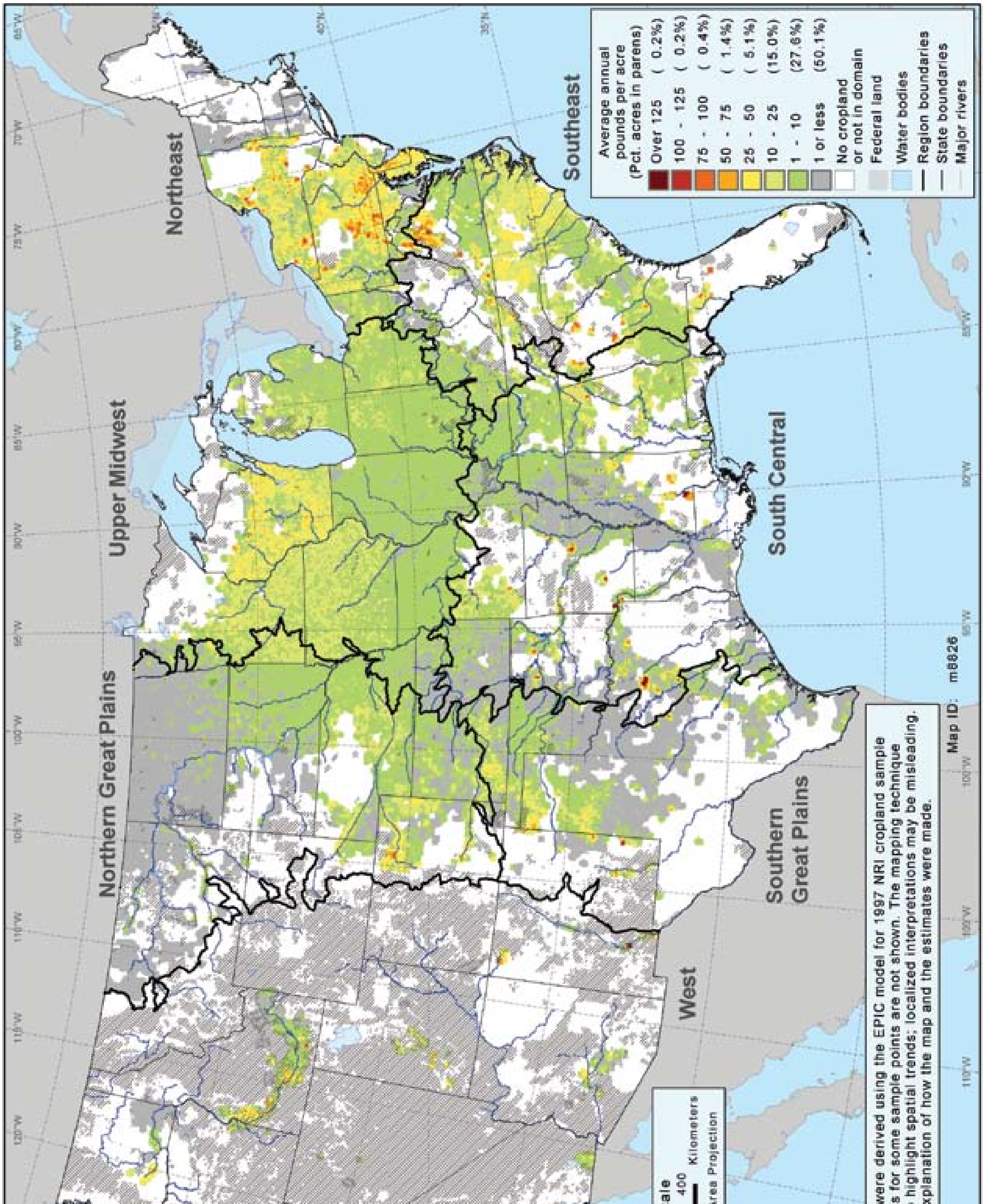


Figure 14 Sources of per-acre nitrogen inputs–by region

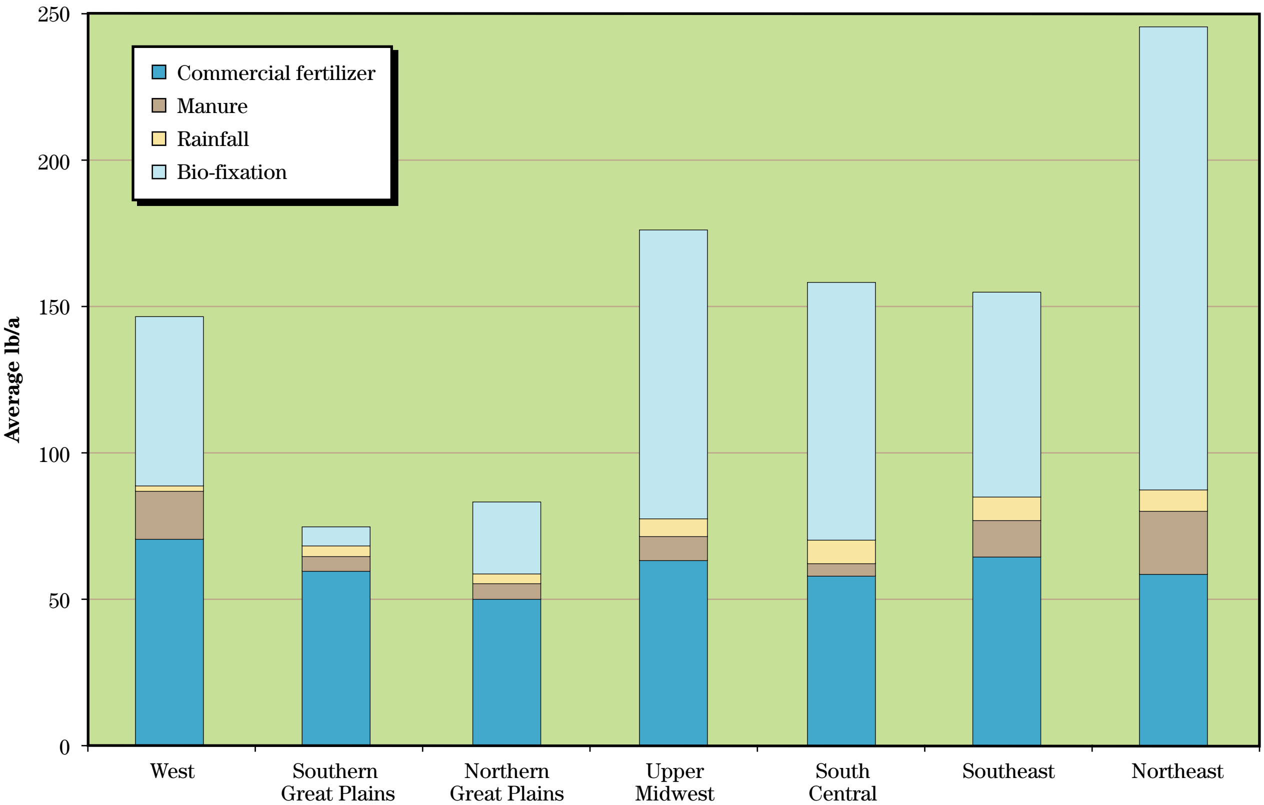


Table 34 Sources of nitrogen inputs on a per-acre basis–by region and by crop within regions (average annual values)

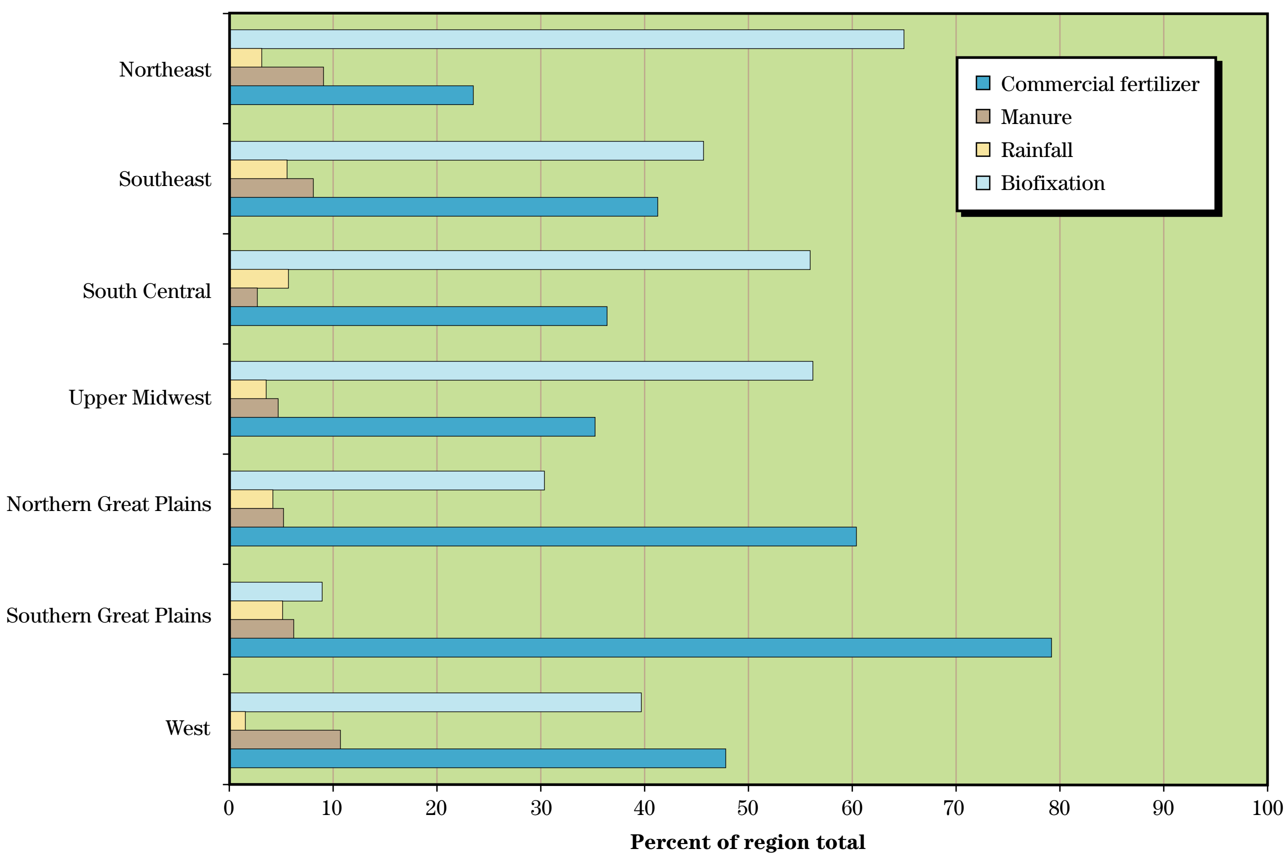
Region	Crop	Acres (1,000s)	Commercial fertilizer (lb/a)	Manure (lb/a)	Atmospheric deposition (lb/a)	Bio-fixation (lb/a)	Sum of inputs (lb/a)
By region							
Northeast	All crops	13,642	57.0	21.5	7.1	158.6	244.2
Northern Great Plains	All crops	72,397	50.1	4.3	3.4	25.1	82.9
South Central	All crops	45,350	56.9	3.8	8.7	87.9	157.3
Southeast	All crops	13,394	63.3	12.3	8.3	70.0	153.9
Southern Great Plains	All crops	32,096	59.4	4.6	3.8	6.6	74.5
Upper Midwest	All crops	112,581	62.3	8.3	6.1	99.1	175.8
West	All crops	9,018	70.7	15.9	2.3	58.4	147.3
All regions	All crops	298,478	58.3	7.3	5.6	69.7	141.0
By crop within region*							
Northeast	Corn	2,943	85.3	27.1	7.2	0.0	119.6
	Corn silage	1,482	64.5	113.7	7.0	0.0	185.2
	Grass hay	2,369	63.6	6.4	7.0	0.0	77.0
	Legume hay	4,052	35.9	0.9	6.9	485.1	528.9
	Oats	362	52.4	1.0	7.0	0.0	60.3
	Soybeans	1,305	31.7	16.8	7.5	151.3	207.4
	Winter wheat	853	53.3	3.4	7.4	0.0	64.1
Northern Great Plains	Barley	3,243	78.4	0.3	3.0	0.0	81.8
	Corn	15,466	101.2	13.7	3.7	0.0	118.6
	Corn silage	810	69.6	67.0	3.5	0.0	140.1
	Grass hay	2,443	64.5	3.4	3.2	0.0	71.1
	Legume hay	6,152	35.9	1.1	3.3	168.7	209.0
	Oats	1,255	17.9	0.1	3.3	0.0	21.3
	Spring wheat	18,916	39.0	0.0	3.1	0.0	42.1
	Sorghum	1,595	79.8	4.7	3.6	0.0	88.2
	Soybeans	9,562	2.9	1.0	3.7	81.4	89.0
	Winter wheat	12,748	34.9	0.7	3.3	0.0	38.9
South Central	Corn	5,956	125.1	7.4	9.1	0.0	141.7
	Cotton	5,487	81.1	0.4	9.4	0.0	90.9
	Grass hay	3,347	55.9	24.6	8.3	0.0	88.8
	Legume hay	1,630	35.8	0.8	8.2	533.3	578.1
	Peanuts	880	13.9	2.1	9.3	79.3	104.5
	Rice	3,004	121.1	0.0	9.7	0.0	130.8
	Sorghum	2,729	83.4	2.0	7.4	0.0	92.9
	Soybeans	14,083	4.7	1.4	9.1	216.4	231.6
	Winter wheat	7,896	57.5	0.3	7.4	0.0	65.1

Table 34 Sources of nitrogen inputs on a per-acre basis–by region and by crop within regions (average annual values)—Continued

Region	Crop	Acres (1,000s)	Commercial fertilizer (lb/a)	Manure (lb/a)	Atmospheric deposition (lb/a)	Bio-fixation (lb/a)	Sum of inputs (lb/a)
Southeast	Corn	3,028	121.9	16.3	8.3	0.0	146.6
	Corn silage	412	105.7	69.3	8.0	0.0	183.1
	Cotton	2,422	63.0	1.9	8.7	0.0	73.6
	Grass hay	2,000	58.5	19.1	8.1	0.0	85.7
	Legume hay	1,183	35.9	1.1	7.7	478.7	523.5
	Peanuts	479	13.5	2.9	8.9	77.6	102.8
	Soybeans	2,419	12.2	14.2	8.4	137.9	172.7
	Winter wheat	1,216	55.9	4.6	8.3	0.0	68.9
Southern Great Plains	Corn	2,665	116.1	36.4	3.8	0.0	156.3
	Cotton	7,316	43.5	0.2	3.6	0.0	47.3
	Legume hay	677	35.8	2.8	3.3	256.5	298.5
	Oats	503	16.8	0.4	4.9	0.0	22.0
	Peanuts	484	33.2	0.1	4.2	41.3	78.8
	Sorghum	4,895	81.0	3.4	4.0	0.0	88.4
	Winter wheat	15,037	53.2	1.0	3.9	0.0	58.0
Upper Midwest	Corn	47,941	114.2	12.6	6.2	0.0	133.0
	Corn silage	1,947	63.8	136.8	5.7	0.0	206.4
	Grass hay	4,044	64.4	4.0	6.1	0.0	74.6
	Legume hay	9,233	35.9	0.8	5.8	420.8	463.4
	Oats	1,388	18.9	0.3	5.6	0.0	24.8
	Spring wheat	815	81.3	0.2	4.9	0.0	86.4
	Sorghum	1,604	82.4	1.2	6.0	0.0	89.6
	Soybeans	40,049	3.0	0.8	6.2	181.6	191.7
	Winter wheat	5,147	82.5	0.2	6.3	0.0	89.1
West	Barley	958	60.2	2.5	2.2	0.0	64.8
	Corn silage	297	78.1	202.1	2.6	0.0	282.9
	Cotton	1,631	125.4	10.2	1.8	0.0	137.5
	Legume hay	1,847	35.5	7.5	1.8	285.2	330.1
	Potatoes	329	214.4	3.1	1.9	0.0	219.4
	Rice	599	22.8	0.0	3.1	0.0	25.9
	Spring wheat	772	55.7	10.5	2.1	0.0	68.3
	Winter wheat	2,118	58.4	8.4	2.8	0.0	69.6

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Figure 15 Sources of nitrogen inputs as a percent of the regional total



Northern Great Plains and Southern Great Plains. On a per-acre basis, nitrogen inputs were lowest for the Northern Great Plains and Southern Great Plains regions for almost all sources (fig. 14, table 34), averaging 83 and 75 pounds of nitrogen per acre, respectively. This was largely because of the small acreage of nitrogen bio-fixing legume crops. Commercial fertilizer accounted for the bulk of the nitrogen inputs in these two regions (fig. 15); manure nitrogen and atmospheric deposition each accounted for about 5 percent of the total inputs.

West region. Total nitrogen input for the West region averaged 147 pounds per acre (table 34, fig. 14). The largest source was commercial fertilizer at 48 percent, followed by bio-fixation at 40 percent, manure at 11 percent, and atmospheric deposition at 1.6 percent (fig. 15). The West region had the lowest amount of nitrogen from atmospheric deposition, averaging only 2.3 pounds per acre in these model simulations.

Nitrogen input estimates by crop

Of all the crops, alfalfa hay had the highest per-acre amount of nitrogen inputs in these model simulations, mostly consisting of bio-fixation (fig. 16, table 34). Corn silage and soybeans were the next highest. Nitrogen for soybeans was almost entirely bio-fixation, whereas manure was the dominant source for corn silage. Commercial nitrogen fertilizer application rates varied from crop to crop, with the highest rates for potatoes, rice, and corn, and the lowest for soybeans (fig. 16). Commercial nitrogen fertilizer accounted for 80 percent or more of the nitrogen inputs for all but corn silage and the three legume crops. About 60 percent of the nitrogen sources for corn silage came from manure. Manure was a significant source on a per-acre basis for only three crops—corn silage, corn, and grass hay—resulting directly from assumptions used to derive the manure application database.

Model simulation results for nitrogen loss

Of the 21 million tons per year of nitrogen inputs represented in the EPIC model simulations, about 28 percent—6 million tons—was lost from the field through volatilization, dissolved in surface water runoff, leaching, or carried away with the soil by wind and water erosion (table 35). Most nitrogen was lost through volatilization—47 percent, equivalent to an average per acre loss of 18.5 pounds per year. The next highest loss pathway, accounting for 21 percent of total nitrogen loss, was nitrogen lost with waterborne sediment, which averaged 8.5 pounds per cropland acre per year (table 35, table 23). Nitrogen dissolved in leachate was the third highest loss category, averaging 6.7 pounds per acre per year and representing 17 percent of total nitrogen losses. Nitrogen dissolved in surface water runoff averaged 3.8 pounds per acre per year and accounted for 10 percent of total nitrogen loss. On average for all cropland, windborne nitrogen loss with sediment accounted for about 4 percent of nitrogen loss, and nitrogen lost from the field through lateral subsurface flow accounted for only about 1 percent. The average for all nitrogen loss pathways combined was about 40 pounds per acre per year (table 36).

Map 15 shows the distribution of the sum of nitrogen loss from all six pathways. The most vulnerable areas for overall loss of nitrogen from farm fields are colored red and brown in the map, and represent about 9 percent of the cropland acres. In these areas, the loss of nitrogen from farm fields averages over 72 pounds per acre per year. These highly vulnerable cropland acres are scattered throughout various parts of the country, but tend to be concentrated mostly in Iowa, Indiana, Pennsylvania, the Atlantic Coastal Plain, Lower Mississippi River Basin, and southeastern Texas. The least vulnerable acres, represented in green on the map, comprise 59 percent of the cropland acres and have total nitrogen loss rates below 36 pounds per acre per year, on average.

The potential for nitrogen loss varied considerably among cropland acres, reflecting variability in the amounts lost through each of the six nitrogen loss pathways, variability in nitrogen lost among soils with different properties, variability in the amount and kind of nitrogen sources by crop, the extent to which conservation tillage occurred, and the extent to which the three conservation practices included in the model simulation were present.

Per-acre nitrogen loss estimates for six loss pathways

The spatial distribution of nitrogen loss for each of the nitrogen loss pathways (except lateral subsurface flow) is shown in maps 16 through 20. The class breaks for maps 16 through 20 are the same so that comparisons can be made among the maps. It is clear from these maps that there is considerable variability within cropland as to which loss pathways account

Figure 16 Sources of per-acre nitrogen inputs–by crop

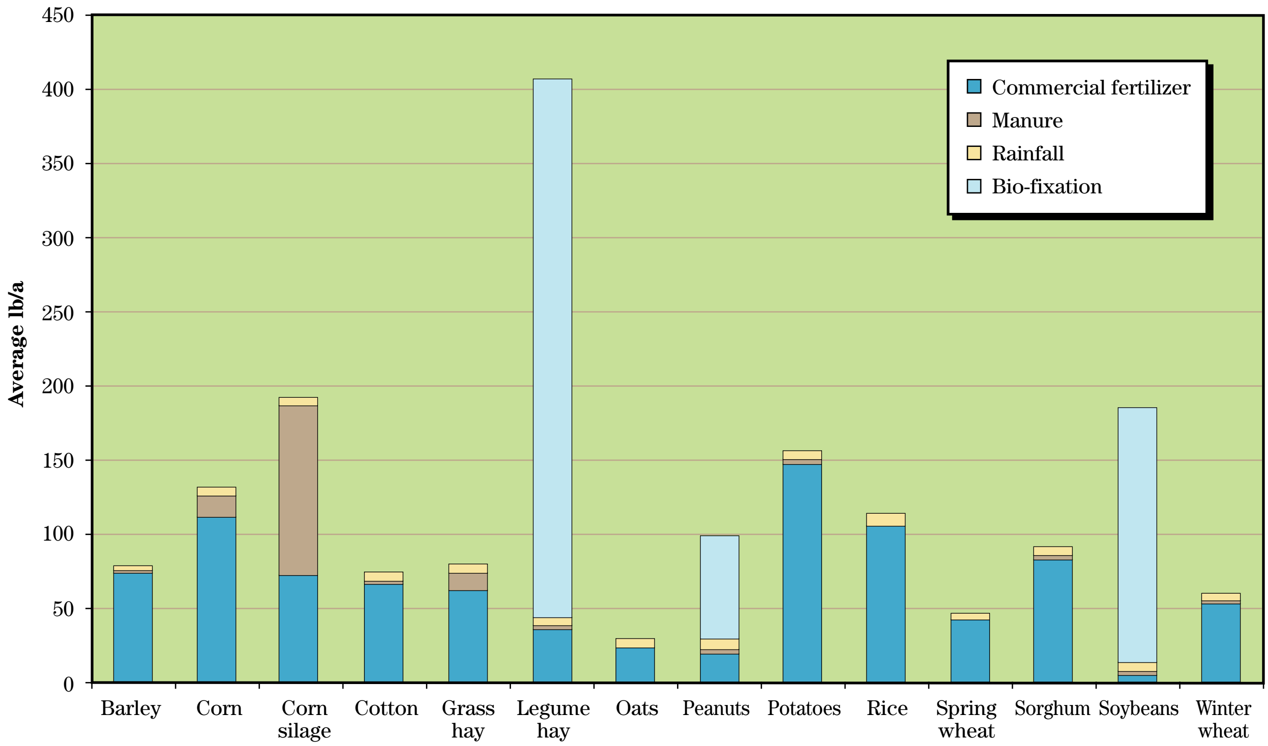


Table 35 Nitrogen loss estimates–by region and by crop (annual average values)

	Acres	Volatilized		Dissolved in surface water runoff		Dissolved in leachate		Dissolved in lateral subsurface flow		Lost with waterborne sediment		Lost with windborne sediment		Sum of all loss pathways	
	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
By region															
Northeast	4.6	78,711	2.9	45,275	7.9	46,457	4.7	4,604	7.0	91,141	7.2	1,060	0.4	267,281	4.5
Northern Great Plains	24.3	596,583	21.6	64,928	11.4	36,852	3.7	11,222	17.0	164,394	12.9	131,371	49.4	1,005,360	17.0
South Central	15.2	398,622	14.5	174,590	30.6	304,219	30.5	11,747	17.8	247,942	19.5	9,657	3.6	1,146,779	19.3
Southeast	4.5	170,688	6.2	26,587	4.7	200,291	20.1	5,934	9.0	47,604	3.7	86	<0.1	451,191	7.6
Southern Great Plains	10.8	438,673	15.9	27,384	4.8	61,394	6.1	4,089	6.2	41,002	3.2	103,231	38.8	675,785	11.4
Upper Midwest	37.7	996,009	36.1	159,552	28.0	339,126	34.0	27,060	41.0	665,135	52.4	19,473	7.3	2,206,378	37.2
West	3.0	76,795	2.8	72,026	12.6	10,298	1.0	1,399	2.1	12,301	1.0	1,047	0.4	173,956	2.9
All regions	100.0	2,756,079	100.0	570,341	100.0	998,637	100.0	66,055	100.0	1,269,517	100.0	265,924	100.0	5,926,729	100.0
By crop															
Barley	1.6	52,993	1.9	12,562	2.2	1,765	0.2	1,235	1.9	11,585	0.9	6,659	2.5	86,798	1.5
Corn	26.2	956,074	34.7	124,161	21.8	389,473	39.0	25,796	39.1	562,179	44.3	92,247	34.7	2,149,929	36.3
Corn silage	1.7	46,467	1.7	15,244	2.7	20,805	2.1	2,448	3.7	56,684	4.5	5,058	1.9	146,705	2.5
Cotton	5.6	101,326	3.7	55,777	9.8	114,922	11.5	2,574	3.9	51,654	4.1	48,920	18.4	375,172	6.3
Grass hay	4.9	59,044	2.1	66,011	11.6	4,287	0.4	1,660	2.5	13,986	1.1	34	<0.1	145,023	2.4
Legume hay	8.3	152,594	5.5	67,735	11.9	5,340	0.5	2,555	3.9	781	0.1	13	<0.1	229,193	3.9
Oats	1.3	18,264	0.7	3,289	0.6	4,435	0.4	512	0.8	14,784	1.2	2,515	0.9	43,797	0.7
Peanuts	0.6	16,915	0.6	3,124	0.5	40,268	4.0	1,637	2.5	3,957	0.3	2,455	0.9	68,355	1.2
Potatoes	0.3	20,253	0.7	8,181	1.4	21,245	2.1	785	1.2	4,006	0.3	1,710	0.6	56,178	0.9
Rice	1.2	11,869	0.4	60,612	10.6	39,659	4.0	177	0.3	13,268	1.0	60	<0.1	125,643	2.1
Spring wheat	6.9	129,671	4.7	21,068	3.7	1,248	0.1	1,666	2.5	48,548	3.8	29,990	11.3	232,189	3.9
Sorghum	3.7	147,017	5.3	10,851	1.9	30,979	3.1	2,495	3.8	36,176	2.8	34,269	12.9	261,785	4.4
Soybeans	22.6	581,091	21.1	90,757	15.9	282,995	28.3	17,786	26.9	352,233	27.7	24,865	9.4	1,349,726	22.8
Winter wheat	15.1	462,504	16.8	30,973	5.4	41,217	4.1	4,733	7.2	99,679	7.9	17,133	6.4	656,238	11.1
All crops	100.0	2,756,079	100.0	570,341	100.0	998,637	100.0	66,055	100.0	1,269,517	100.0	265,924	100.0	5,926,729	100.0

Table 36 Nitrogen loss estimates on a per-acre basis–by region and by crop within regions (average annual values)

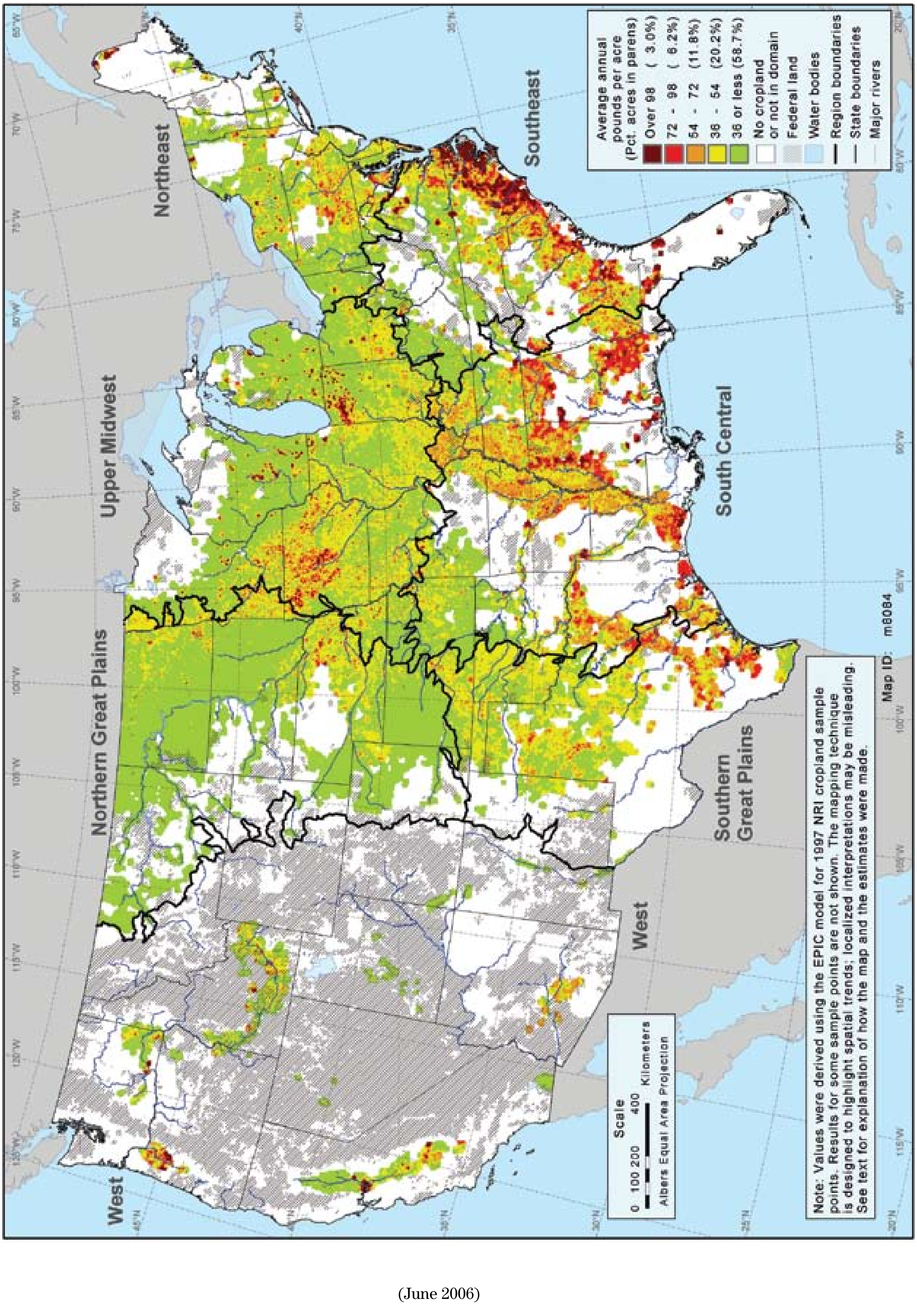
Region	Crop	Acres (1,000s)	Volatilized (lb/a)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Dissolved in lateral subsurface flow (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Sum of all loss pathways (lb/a)
By region									
Northeast	All crops	13,642	11.5	6.6	6.8	0.7	13.4	0.2	39.2
Northern Great Plains	All crops	72,397	16.5	1.8	1.0	0.3	4.5	3.6	27.8
South Central	All crops	45,350	17.6	7.7	13.4	0.5	10.9	0.4	50.6
Southeast	All crops	13,394	25.5	4.0	29.9	0.9	7.1	<0.1	67.4
Southern Great Plains	All crops	32,096	27.3	1.7	3.8	0.3	2.6	6.4	42.1
Upper Midwest	All crops	112,581	17.7	2.8	6.0	0.5	11.8	0.3	39.2
West	All crops	9,018	17.0	16.0	2.3	0.3	2.7	0.2	38.6
All regions	All crops	298,478	18.5	3.8	6.7	0.4	8.5	1.8	39.7
By crop within region*									
Northeast	Corn	2,943	12.6	3.2	11.8	0.9	23.3	0.3	52.1
	Corn silage	1,482	10.4	5.4	8.5	1.2	40.9	0.4	66.9
	Grass hay	2,369	6.8	15.5	0.8	0.3	4.2	<0.1	27.5
	Legume hay	4,052	13.5	7.0	1.3	0.4	0.1	<0.1	22.2
	Oats	362	8.1	4.3	4.7	0.7	17.7	0.1	35.7
	Soybeans	1,305	13.8	2.9	17.4	1.0	13.3	0.3	48.6
	Winter wheat	853	11.5	2.3	1.9	0.4	15.2	0.1	31.2
Northern Great Plains	Barley	3,243	26.7	3.2	0.2	0.5	4.7	3.9	39.1
	Corn	15,466	28.2	2.7	3.6	0.8	8.0	7.7	50.9
	Corn silage	810	20.3	3.1	2.3	0.7	9.0	7.7	43.1
	Grass hay	2,443	5.3	6.6	<0.1	0.1	0.4	<0.1	12.4
	Legume hay	6,152	12.0	3.0	0.1	0.1	0.1	<0.1	15.2
	Oats	1,255	8.8	0.7	0.2	0.2	5.2	3.3	18.3
	Spring wheat	18,916	12.6	1.4	0.1	0.2	4.8	3.1	22.1
	Sorghum	1,595	26.3	1.4	1.4	0.7	6.0	7.7	43.5
	Soybeans	9,562	13.3	0.5	0.7	0.2	5.7	3.7	24.2
	Winter wheat	12,748	10.9	0.4	0.1	0.1	1.5	0.9	14.0
South Central	Corn	5,956	18.3	8.4	13.1	0.7	19.1	0.6	60.2
	Cotton	5,487	9.0	5.1	20.7	0.4	12.4	0.1	47.6
	Grass hay	3,347	9.3	4.8	0.6	0.2	2.1	<0.1	17.0
	Legume hay	1,630	10.8	3.2	0.4	0.2	0.1	<0.1	14.8
	Peanuts	880	18.9	2.8	50.2	2.2	4.8	0.6	79.6
	Rice	3,004	6.9	37.8	24.5	0.1	8.6	<0.1	77.9
	Sorghum	2,729	17.4	2.8	8.5	0.4	11.1	2.6	42.8
	Soybeans	14,083	25.1	7.8	17.4	0.7	12.4	0.4	63.8
	Winter wheat	7,896	18.7	1.9	2.9	0.3	8.4	0.2	32.4

Table 36 Nitrogen loss estimates on a per-acre basis–by region and by crop within regions (average annual values)—Continued

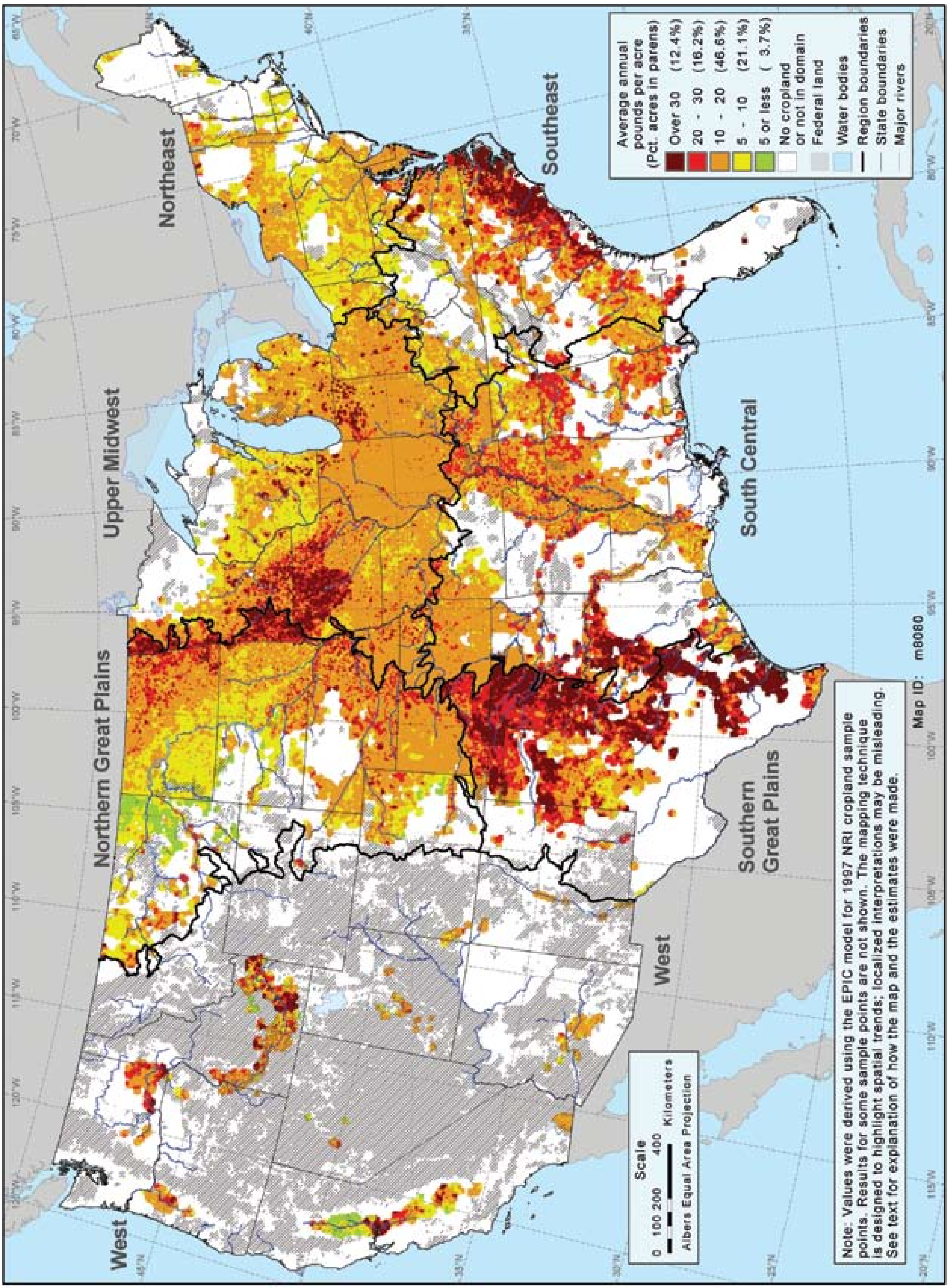
Region	Crop	Acres (1,000s)	Volatilized (lb/a)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Dissolved in lateral subsurface flow (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Sum of all loss pathways (lb/a)
Southeast	Corn	3,028	45.6	5.0	51.0	1.1	12.5	<0.1	115.2
	Corn silage	412	22.4	6.6	18.3	1.7	20.4	<0.1	69.5
	Cotton	2,422	10.7	2.1	26.6	0.6	5.6	<0.1	45.7
	Grass hay	2,000	12.4	5.5	2.2	0.3	2.5	<0.1	22.9
	Legume hay	1,183	12.5	5.2	1.6	0.4	0.1	<0.1	19.8
	Peanuts	479	18.4	2.7	55.5	1.8	5.4	<0.1	83.8
	Soybeans	2,419	31.3	3.4	41.6	1.4	5.8	<0.1	83.6
	Winter wheat	1,216	33.1	2.2	23.1	0.7	9.8	<0.1	68.8
Southern Great Plains	Corn	2,665	30.4	5.6	4.3	0.4	4.9	12.4	57.9
	Cotton	7,316	14.5	2.1	6.5	0.2	2.9	13.3	39.4
	Legume hay	677	15.4	3.7	0.1	0.1	<0.1	<0.1	19.2
	Oats	503	20.8	1.4	6.2	0.3	3.3	0.6	32.6
	Peanuts	484	17.3	5.0	20.1	1.0	2.3	9.1	54.8
	Sorghum	4,895	36.6	1.8	5.9	0.3	3.1	9.9	57.5
	Winter wheat	15,037	31.5	0.5	1.4	0.2	1.9	1.3	37.0
Upper Midwest	Corn	47,941	23.0	2.3	9.3	0.6	16.0	0.6	51.7
	Corn silage	1,947	19.3	3.2	7.5	0.8	16.6	0.7	48.0
	Grass hay	4,044	7.2	12.8	0.1	0.2	1.2	<0.1	21.5
	Legume hay	9,233	11.0	7.6	0.2	0.2	<0.1	<0.1	19.1
	Oats	1,388	6.7	1.1	0.8	0.2	9.0	0.4	18.2
	Spring wheat	815	17.5	5.4	0.1	0.1	5.5	0.8	29.5
	Sorghum	1,604	15.4	1.6	4.1	0.6	10.6	0.4	32.8
	Soybeans	40,049	14.6	1.4	4.8	0.5	11.1	0.2	32.5
	Winter wheat	5,147	14.8	3.1	0.6	0.2	8.9	0.1	27.8
West	Barley	958	14.8	13.5	0.8	0.8	4.8	0.5	35.2
	Corn silage	297	30.4	29.6	8.8	0.4	2.7	0.2	72.2
	Cotton	1,631	13.0	38.9	2.8	0.1	0.4	<0.1	55.3
	Legume hay	1,847	17.4	2.4	0.1	<0.1	0.1	<0.1	20.1
	Potatoes	329	56.1	38.7	10.0	2.1	0.6	1.4	108.9
	Rice	599	3.9	11.9	6.7	<0.1	1.0	<0.1	23.5
	Spring wheat	772	9.0	15.6	0.7	0.4	3.3	0.5	29.5
	Winter wheat	2,118	17.9	6.0	1.7	0.2	6.6	0.3	32.7

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Map 15 Estimated average annual per-acre nitrogen loss summed over all loss pathways



Map 16 Estimated average annual per-acre nitrogen lost to the atmosphere



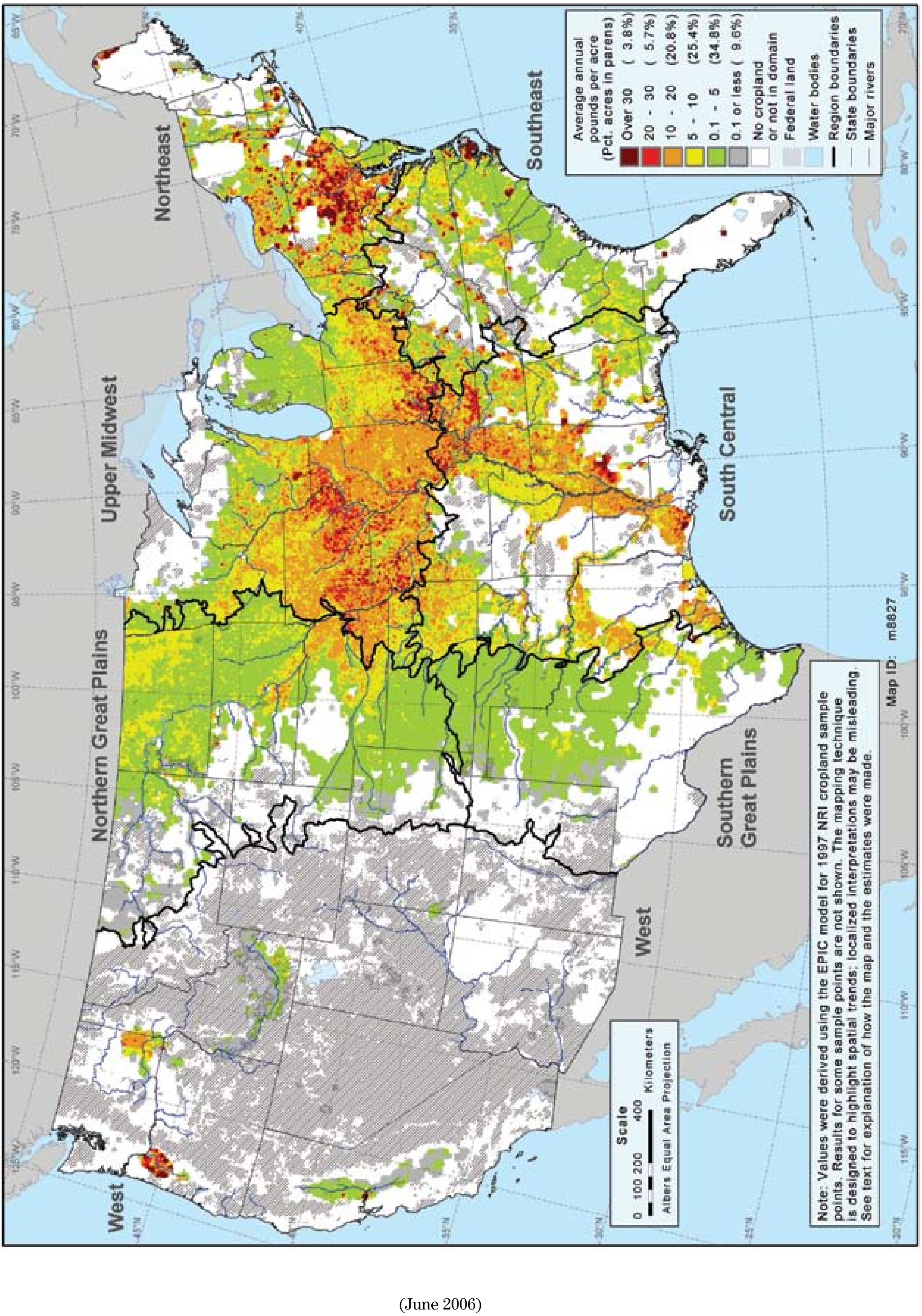
Geographic boundaries are sometimes evident on maps

Geographic boundaries such as state boundaries or climate zone boundaries are sometimes evident on the maps of model output. The sharp boundaries are not real, but rather are a modeling artifact. They are due to the use of highly aggregated input data on nutrient applications or due to adjacent climate zones with very different weather parameters. For example, several state boundaries and climate zone boundaries are evident in maps 15 and 16. There are sharp differences shown in model output along the state border between Minnesota and bordering states to the west. Climate zone boundary effects occur in parts of Nebraska, Kansas, and Texas. These boundary effects show up in other maps, as well.

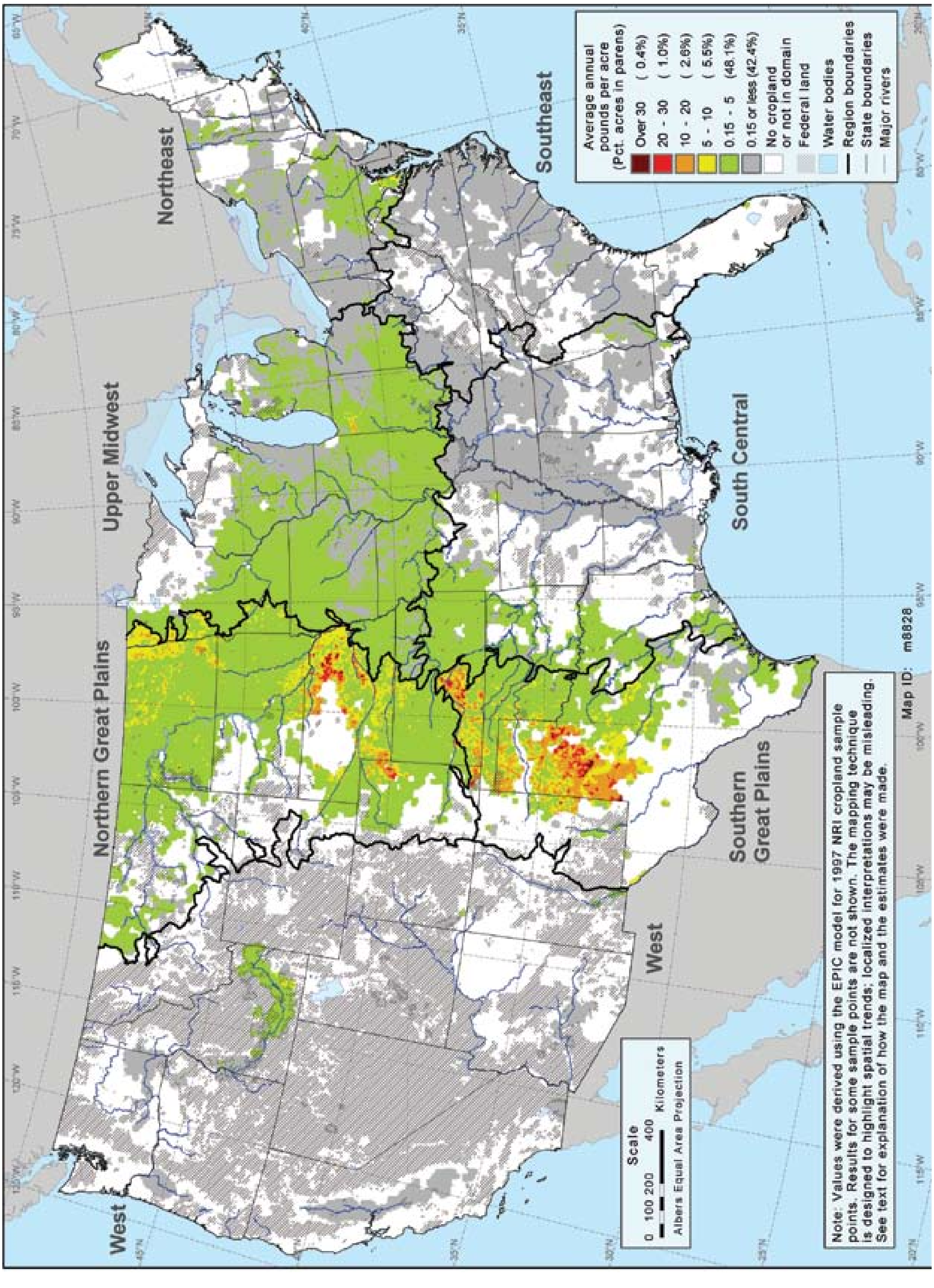
The origin of the state boundary effects is evident from the maps on nitrogen and phosphorus commercial fertilizer and manure application rates (see maps 13–14 and 26–27). Commercial fertilizer application data were derived from farmer surveys and aggregated to the state level or sometimes combinations of states for each crop. Manure application data were derived from the Census of Agriculture farm-level data and aggregated to the state-climate zone level for each crop. Thus, all NRI sample points for a particular crop in a particular state-climate zone area were modeled with the same average nutrient application inputs, which were sometimes markedly different from average nutrient application inputs in an adjoining state.

The origin of the climate zone boundaries is evident from the climate zone map (map 4). Most of the climate zones outside of the West region are very large, creating marked differences between climate zones in the data inputs used in the EPIC model to calculate precipitation (map 5) and surface water runoff (map 7). These climate zones boundaries are sometimes apparent in maps of model output heavily influenced by surface water runoff. The map of nitrogen lost with waterborne sediment (map 17), for example, shows climate zone boundary effects in the Great Plains regions.

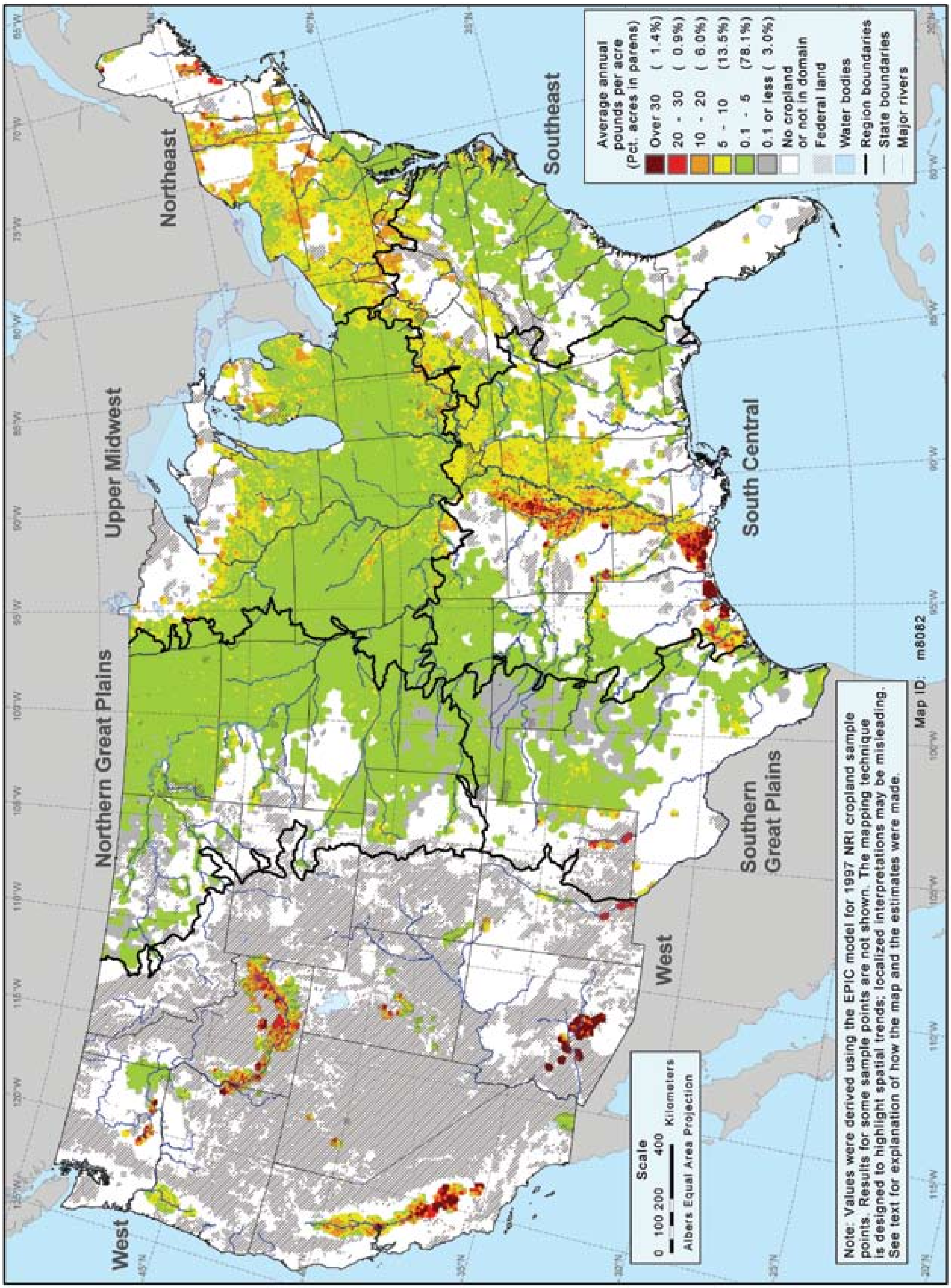
Map 17 Estimated average annual per-acre nitrogen lost with waterborne sediment



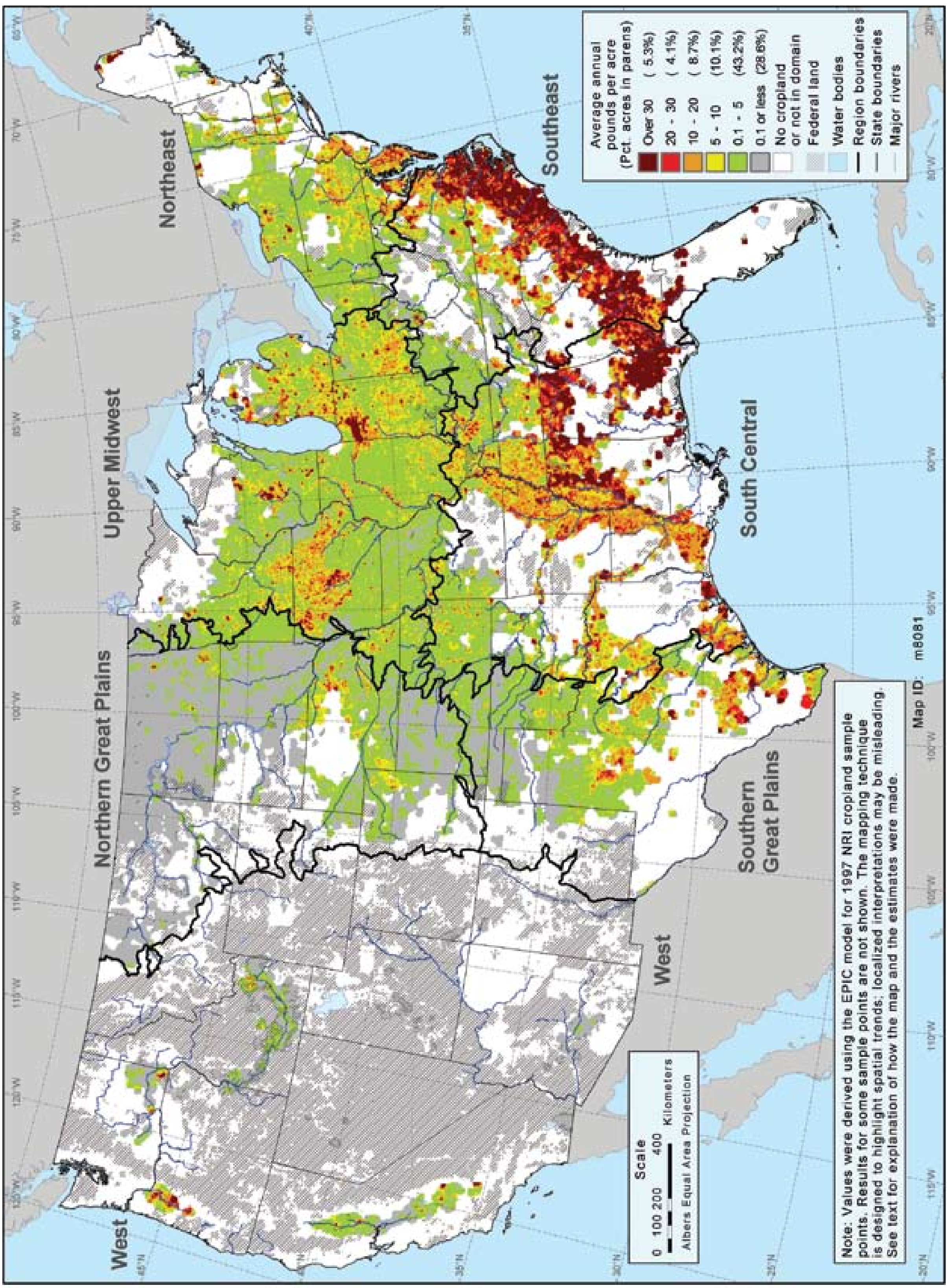
Map 18 Estimated average annual per-acre nitrogen lost with windborne sediment



Map 19 Estimated average annual per-acre nitrogen dissolved in surface water runoff



Map 20 Estimated average annual per-acre nitrogen dissolved in leachate



Visual distortion of cropland acres in per-acre maps

The mapping technique used to display per-acre model output results was developed specifically to show spatial trends, thereby identifying cropland areas with specific resource concerns. There are three steps involved in the mapping technique (see figs. 5 and 6):

Step 1. Calculate the average value for each 25-square kilometer (9.6 mi^2) grid cell using the model output for each NRI sample point located in the grid cell.

Step 2. Interpolate values to surrounding cells that have no NRI sample points.

Step 3. Perform a geographic transformation that smoothes the representation of the results.

While these steps enhance spatial trends, they also produce some distortion of the extent to which cropland acres are represented.

The biggest source of distortion stems from use of grid cells to represent NRI attributes. Some grid cells contain only a few NRI sample points, representing only a few acres of cropland. This is common in areas of the country where cropland is not the dominant land use. In areas where cropland is concentrated, each grid cell will represent many more cropland acres. Since all grid cells are the same size, this has the visual effect of exaggerating the cropland representation in some areas of the country relative to other areas of the country. Areas where cropland is a small share of the land use on the landscape appear over-represented in the maps.

Map 20 provides an example of this kind of distortion. The Atlantic Coastal Plain shows prominently on the map as a large area of high vulnerability to nitrogen dissolved in leachate. Most mapping cells in this area had average per acre values of over 30 pounds per acre—the highest class shown on the map. While cropland acres in this area are highly vulnerable to nitrogen leaching, less than 40 percent of the acres in that area are cropland acres. Overall, only 5.3 percent of the cropland acres included in the study had nitrogen leaching estimates above 30 pounds per acre, as shown in the legend for map 20. The visual representation leaves the impression that many more acres are vulnerable than there actually were.

The interpolation step further exaggerates the representation of cropland acres in areas of the map where cropland is a minor land use. This source of distortion is explained in figure 7. The visual impression of the extent of the vulnerable acres in the Atlantic Coastal Plain in map 20 is also affected by interpolation along the edges of the cropland areas.

The percentage of acres associated with the class breaks used to construct the maps is reported in the map legend to provide a perspective on the extent of the over-representation of acres in the maps. These percentages were calculated on the basis of the individual NRI sample points, and not on the basis of the average values for the map cells. Thus, the percentages reported in the map legend do not account for the “averaging effect” originating from use of the mean values to represent model output for each map cell.

for the bulk of the nitrogen loss in a particular area or even an entire region. This variability stems from the spatial variability among the various factors that effect nitrogen loss. Areas of greatest vulnerability did not always correspond to areas with the highest nitrogen inputs (maps 13 and 14), indicating the importance of the physical setting in nutrient loss dynamics.

Nitrogen volatilization. Loss of nitrogen to the atmosphere through volatilization was high for nearly all cropland acres (map 16), and was the highest loss pathway for the vast majority of acres. On the basis of model simulation results shown in map 16, the regions of greatest vulnerability for nitrogen volatilization—colored brown and red—are:

- A broad area in Oklahoma and Texas, which includes most of the cropland in those two states. In this area, volatilization losses appear to result from the prevalence of calcareous alkaline soils, high temperatures, strong winds, and lengthy dry periods. In the model simulations, fertilizers were applied according to a set activity schedule and were not adjusted to reflect dry periods and associated periods of depressed crop growth, which might partly explain the high nitrogen volatilization results obtained with EPIC for this area.
- An area that extends from northern Iowa northward through most of the cropland in Minnesota
- An area along the Mid-Atlantic coast that includes North Carolina and parts of South Carolina
- Cropland acres in the northwest

These vulnerable areas represent about 29 percent of cropland acres included in the study. The least vulnerable areas are colored yellow and green in the map and represent about 25 percent of cropland acres.

Nitrogen lost with waterborne sediment. In general, areas of greatest vulnerability for nitrogen lost with waterborne sediment are about the same as those shown for sediment loss in map 9. Areas of greatest vulnerability—colored brown and red in map 17—represent about 10 percent of the cropland acres included in the study. The area that stands out as the most vulnerable is in Pennsylvania and northern Maryland. An area consisting of cropland acres in Iowa, northern Missouri, and Illinois was also prominent in terms of vulnerable acres for nitrogen lost with waterborne sediment. This area was less prominent in terms of vulnerable acres for sediment loss.

Nitrogen lost with windborne sediment. Areas of greatest vulnerability for nitrogen lost with windborne sediment (map 18) are the same areas that had the highest potential for wind erosion shown in map 11.

Nitrogen dissolved in surface water runoff. The potential for loss of nitrogen dissolved in surface water runoff from farm fields is shown in map 19. For most cropland acres, the per-acre amount of nitrogen dissolved in surface water runoff was much less than nitrogen lost with waterborne sediment. About 78 percent of the cropland acres included in the study—colored green in map 19—had less than 5 pounds per acre of nitrogen dissolved in surface water runoff. Overall, the cropland areas with the highest potential for loss of nitrogen dissolved in surface water runoff—colored brown, red, and orange in the map and representing about 8 percent of the cropland acres included in the study—are:

- intensively irrigated areas in the West
- cropland acres in the lower Mississippi River Basin and the rice growing area that extends into southern Louisiana and southeastern Texas
- Northeast region
- northern edge of cropland in Minnesota, Wisconsin, and Michigan

In general, cropland areas with the highest loss of nitrogen dissolved in surface water runoff correspond to cropland acres with the highest surface water runoff shown in map 7.

Nitrogen dissolved in leachate. The spatial distribution for nitrogen dissolved in leachate (map 20) is quite different from the spatial patterns of nitrogen dissolved in surface water runoff. The spatial distribution generally corresponds to spatial trends in annual percolation. Most of the cropland acres in regions where percolation exceeds 5 inches per year are associated with elevated levels of nitrogen dissolved in leachate. A notable exception, however, is for a large region in northern Iowa where annual percolation rates are low but where loss of nitrogen in leachate is sometimes high. Intensively irrigated areas in the West and most cropland in the Great Plains have very low

losses of nitrogen dissolved in leachate and also have low levels of percolation. The cropland area of highest percolation in the Southeast, extending from Alabama through Delaware, also has the highest loss of nitrogen dissolved in leachate in the country, usually exceeding rates of 30 pounds per acre per year. Cropland acres with the highest potential for nitrogen dissolved in leachate, represented by the brown and red colored areas in map 20, are:

- Atlantic coastal plain extending from Alabama northward through eastern Virginia and the Delmarva Peninsula
- Lower Mississippi River Basin, including especially cropland in northern Mississippi and Alabama
- cropland in southeastern Texas
- an area in northern Iowa including parts of southern Minnesota
- scattered areas within Michigan, Indiana, western Ohio, and central Wisconsin
- Southern Pennsylvania, New Jersey, and scattered area in New York and the New England states
- Willamette River Basin in Oregon

These vulnerable areas represent about 9 percent of the cropland acres included in the study. Areas of lowest vulnerability for nitrogen dissolved in leachate are colored green in map 20, and represent about 43 percent of the cropland acres included in the study. About 29 percent of the cropland acres had almost no dissolved nitrogen in leachate, shown by the grey areas in map 20.

As explained previously, model simulations did not explicitly account for tile drainage because of the lack of information on the presence or absence of tile drainage fields at NRI sample points. In heavily tiled cropland areas, however, it has been shown that much of the nitrate nitrogen dissolved in leachate that reaches the depth of the tile drainage field returns to surface water via the drainage tiles (Chung et al. 2001, 2002; Fausey et al. 1995; Fischer et al. 1999; Randall and Mulla 2001; Zucker and Brown 1998). Thus it is likely that the vulnerable acres shown in map 20 throughout most of the acreage in the Midwest are actually contributing to nitrogen in surface water runoff via dissolved nitrogen in leachate returning to surface water flows through tile drainage systems.

It is also likely that estimates of nitrogen dissolved in leachate are overstated in cropland areas where surface drainage systems are common because of the mitigating influence of denitrification processes, which were not taken into account in the model simulation. In the Southeast, for example, inherent hardpans and tillage pans can be a hindrance to nitrogen leaching and contribute to short-term waterlogging, resulting in substantial losses of nitrogen via denitrification.

Nitrogen dissolved in lateral subsurface flow. Nitrogen loss through lateral subsurface flow was low in all model simulations, averaging less than 1 pound per acre overall and seldom exceeding 2 pounds per acre in specific model runs. Because of the low amounts lost through this pathway, the spatial distribution is not shown in a map. The ultimate fate of nitrogen loss from the field through lateral subsurface flow cannot be determined by EPIC. Subsurface flow occurs where there is a sloped landscape. After passing the edge of the field, it could return to the surface and contribute to surface water runoff, or it could continue to percolate into the soil as leachate. EPIC model estimates of lateral subsurface flow are not estimates of nitrogen loss through tile drains, although some subsurface lateral flow would be expected to return to surface water through drainage tiles in some situations.

Per-acre nitrogen loss by region

Southeast region. The highest per-acre losses occurred in the Southeast region, where the sum of losses from all loss pathways averaged 67 pounds per acre per year (table 36, fig. 17). Total nitrogen loss in this region represented 44 percent of the annual nitrogen inputs (commercial fertilizer applications, manure applications, bio-fixation, and atmospheric deposition), which was second highest among the seven regions. Most of the nitrogen loss was either nitrogen dissolved in leachate (44%) or nitrogen that volatilized (38%) (fig. 18). Nitrogen loss dissolved in leachate averaged 30 pounds per cropland acre per year—over twice as high as determined for any of the other regions. However, since cropland acres with high water tables are commonly found in areas throughout the Southeast region, a portion of the nitrogen attributed to nitrogen leaching in these model simulations is more likely to volatilize as gaseous nitrogen compounds as a result of de-

Figure 17 Average annual per-acre estimates of nitrogen loss–by region

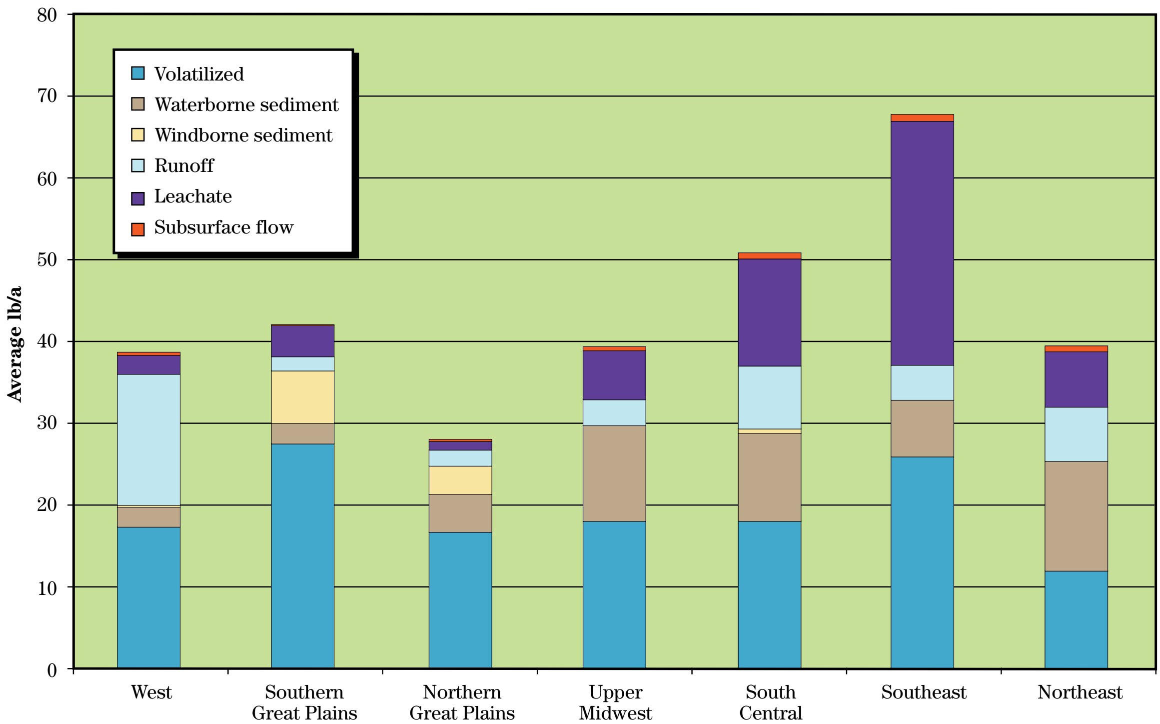
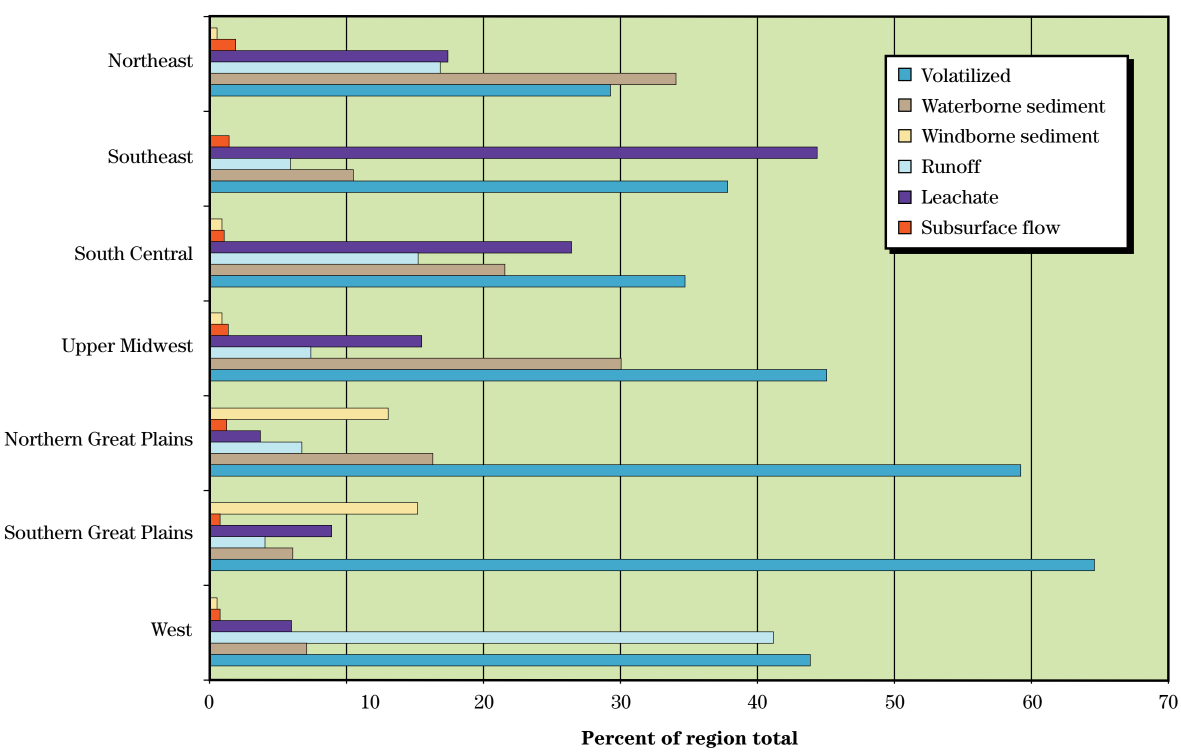


Figure 18 Nitrogen loss as a percentage of the total loss for each region



nitrification, or, in cases where ponding would have occurred, contributed to nitrogen losses in surface water runoff.

Corn acres in the Southeast region had among the highest nitrogen losses of any crop in any of the regions, averaging 115 pounds per acre per year for nitrogen loss summed over all pathways. For corn acres in this region, nitrogen loss dissolved in leachate averaged 51 pounds per acre per year and nitrogen volatilization loss averaged 46 pounds per acre. Nitrogen loss was also high for peanuts and soybeans, each averaging over 80 pounds per acre per year for nitrogen loss summed over all pathways. Nitrogen loss dissolved in leachate was 56 pounds per acre for peanuts in this region, which was the highest average loss for this pathway among all crops in all regions.

South Central region. The South Central region had the second highest per-acre nitrogen loss, averaging 51 pounds per cropland acre per year (table 36, fig. 17). All nitrogen pathways except windborne sediment and lateral subsurface flow had significant losses in the South Central region (fig. 18); the highest losses were due to volatilization and nitrogen dissolved in leachate. Total nitrogen loss in the South Central region represented 32 percent of annual nitrogen inputs.

Peanuts and rice had the highest nitrogen loss rates in this region, each averaging about 80 pounds per acre for nitrogen loss summed over all pathways. The dominant loss pathway for rice was nitrogen dissolved in surface water runoff; nitrogen loss for this pathway averaged 38 pounds per acre, the highest loss for nitrogen dissolved in surface water runoff among all crops and all regions. The dominant loss pathway for peanuts was nitrogen dissolved in leachate, with nitrogen loss for this pathway averaging about 50 pounds per acre per year. Per-acre nitrogen loss was also high for corn and soybean acres in this region, averaging over 60 pounds per acre for nitrogen loss summed over all pathways.

Southern Great Plains region. The Southern Great Plains region had the largest percentage of annual nitrogen inputs lost from farm fields—56 percent. The Southern Great Plains region had the lowest per-acre amount of nitrogen inputs, but had the third highest per-acre nitrogen loss. Model simulations showed that, on average, 42 pounds per acre of nitrogen was lost from cropland acres in this region each year. Nitrogen volatilization was the principal source of nitrogen loss in the region, accounting for 65 percent of all losses (fig. 18). High soil pH, high temperatures, and windy conditions are prevalent in this region, resulting in high rates of nitrogen volatilization. Nitrogen loss with windborne sediment was the second highest loss pathway, accounting for 15 percent of the nitrogen losses. Nitrogen loss with windborne sediment was higher in the Southern Great Plains than in any other region. Other loss pathways in this region were relatively small. Highest losses occurred for corn, sorghum, and peanuts within this region. Nitrogen lost to windborne sediment exceeded 12 pounds per acre, on average, for corn and cotton acres in this region.

Northeast region. Per-acre nitrogen losses in the Northeast region averaged 39 pounds per acre per year, of which waterborne sediment accounted for the largest percentage (34 percent) (figs. 17 and 18). Losses from volatilization accounted for 29 percent, and losses dissolved in runoff and leachate each accounted for 17 percent. The Northeast region had the lowest percentage loss of nitrogen inputs—16 percent—but also had the highest nitrogen inputs among the seven regions.

Corn silage had the highest nitrogen losses among crops in the Northeast, averaging 67 pounds per acre per year for the sum of losses from all pathways. Nitrogen lost with waterborne sediment averaged 41 pounds per acre for corn in this region, the highest per-acre loss for this pathway among all crops in all regions. Corn had the second highest nitrogen loss in the region, averaging 52 pounds per acre per year for the sum of losses over all pathways.

Upper Midwest region. Nitrogen loss in the Upper Midwest region averaged 39 pounds per cropland acre per year, slightly lower than in the Southern Great Plains and about the same as the Northeast and West regions. The dominant nitrogen loss pathways were volatilization (45%) and waterborne sediment (30%) (fig. 18). Highest losses occurred for corn and corn silage. Nitrogen loss in the Upper Midwest represented only 22 percent of the annual nitrogen inputs, which was second to the Northeast region in being the lowest percentage among all the regions.

West region. The West region averaged about 39 pounds per cropland acre of nitrogen losses from all pathways (table 36, fig. 17). These losses represent-

ed 28 percent of the annual nitrogen inputs in this region. Nitrogen loss dissolved in surface water runoff averaged 16 pounds per acre per year and nearly equaled the amount lost through volatilization. These two loss pathways accounted for the majority of nitrogen loss in the region. The percentage of nitrogen loss dissolved in surface water runoff was much higher in the West than in any other region—42 percent (fig. 18). These high losses of nitrogen dissolved in surface water runoff are associated with irrigation practices in the West.

Potatoes had the highest loss of nitrogen in the region, averaging 109 pounds per acre per year for the sum of all loss pathways. An average of 56 pounds per acre per year was due to nitrogen volatilization for potato acres, which is the highest loss for this pathway among all crops and within all regions. Corn silage had the second highest nitrogen loss at 72 pounds per acre for the sum of all loss pathways, followed by cotton at 55 pounds per acre.

Northern Great Plains region. The Northern Great Plains region had the lowest per-acre nitrogen loss at 28 pounds per acre per year for the sum of all loss pathways, consistent with the low level of nitrogen inputs for the region (table 36, fig. 17). Nitrogen losses represented about 34 percent of annual nitrogen inputs in this region. As observed for most regions, nitrogen volatilization accounted for most of the loss, but waterborne sediment and windborne sediment were also significant nitrogen loss pathways in the Northern Great Plains, accounting for 16 and 13 percent of nitrogen losses, respectively. Highest losses occurred for corn acres, which averaged 51 pounds per acre per year for the sum of losses from all pathways.

Per-acre nitrogen loss by crop

The per-acre estimates of nitrogen loss varied by crop, contributing to the diversity of nitrogen loss shown in maps 15 and 16 through 20 because of crop specific differences in nitrogen inputs and management practices.

The highest nitrogen loss on a per-acre basis was for potatoes (averaging 114 lb/a/yr), peanuts (averaging 74 lb/a/yr), and rice (averaging 69 lb/a/yr) (fig. 19). (These three crops also have the lowest cropland acres. As these crops were often minor crops in some regions, regional per-acre estimates of nitrogen loss were not always included in table 36.) For potatoes and peanuts, the dominant loss pathway was nitrogen dissolved in leachate. For rice, the dominant loss pathway was nitrogen dissolved in surface water runoff.

The lowest nitrogen losses were for grass hay and legume hay, averaging less than 20 pounds per acre for nitrogen loss from all pathways. These two crops usually had the lowest nitrogen loss estimates within each region, with regional average losses always less than 30 pounds per acre per year. Oats, spring wheat, and winter wheat also had low nitrogen losses, averaging between 23 and 30 pounds per acre for all acres and averaging less than 37 pounds per acre for all regions except the Southeast region. Nitrogen loss for winter wheat in the Southeast region was 69 pounds per acre per year, where nitrogen volatilization represented about half of the loss.

The overall average loss for the remaining crops—barley, corn, corn silage, cotton, sorghum, and soybeans—ranged from 38 to 56 pounds per acre per year (fig. 19).

Nitrogen loss estimates for irrigated crops often differed from nitrogen loss estimates for non-irrigated crops (table 37). For the sum of nitrogen losses for all pathways, about a third of the estimates were similar, about a third had substantially higher nitrogen losses for irrigated crops, and about a third had substantially lower nitrogen losses for irrigated crops. Examples of crops with substantially lower nitrogen loss estimates for irrigated acres are: sorghum and corn in the Southern Great Plains region, barley in the West region, cotton in the Southeast region, and corn in the Northern Great Plains region. Examples of crops with substantially higher nitrogen loss estimates for irrigated acres are peanuts and legume hay in the Southern Great Plains region and legume hay in the Northern Great Plains region. The largest differences were primarily a reflection of large differences in nitrogen volatilization. For some crops, nitrogen volatilization for non-irrigated crops exceeded nitrogen volatilization for irrigated crops by more than 30 pounds per acre. All irrigated acres had higher estimates of nitrogen dissolved in surface water runoff than non-irrigated acres in these model simulations. In most comparisons, nitrogen dissolved in leachate and nitrogen lost with waterborne sediment were generally similar; where large differences occurred, nitrogen loss from these two pathways was lower for irrigated acres than for non-irrigated acres.

Figure 19 Average annual per-acre estimates of nitrogen loss–by crop

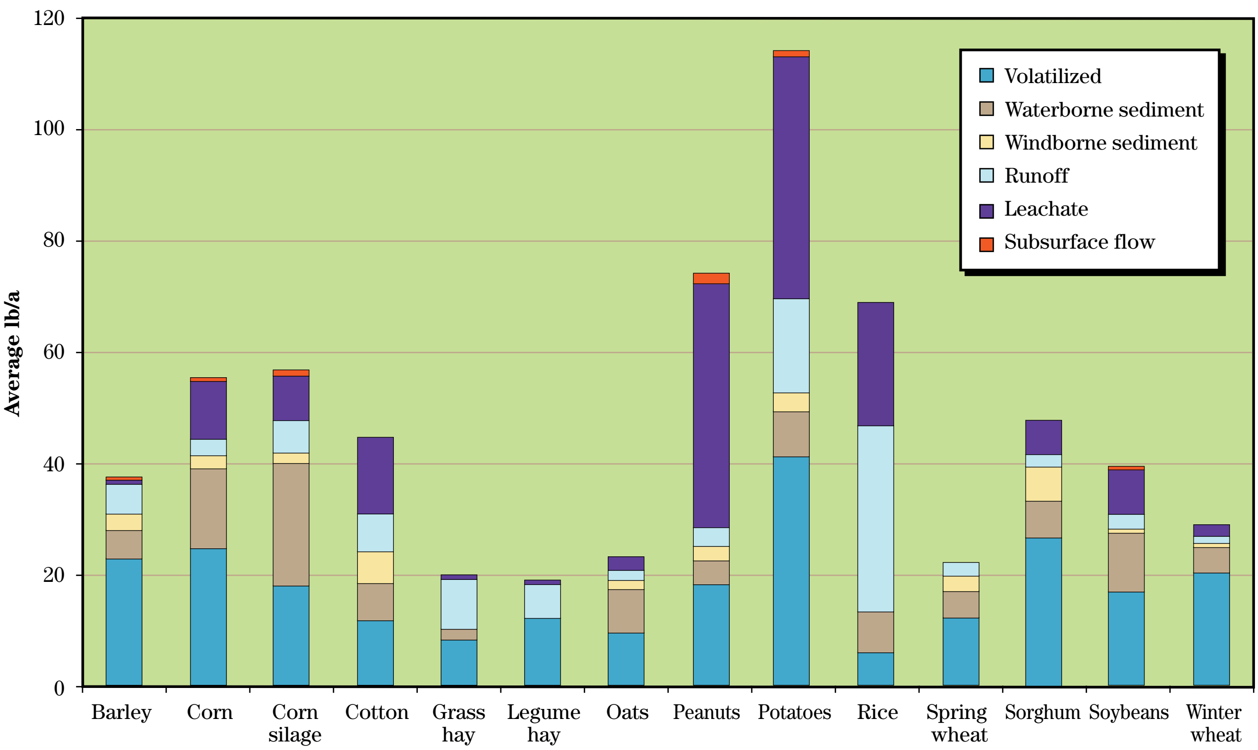


Table 37 Comparison of nitrogen loss estimates for irrigated crops to estimates for non-irrigated crops (average annual values)

		Acres (1,000s)		Sum of all loss pathways** (lb/a)		Volatilized (lb/a)		Dissolved in surface water runoff (lb/a)		Dissolved in leachate (lb/a)		Lost with waterborne sediment (lb/a)	
Region	Crop*	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Northern Great Plains	Corn	6,680	8,785	41.7	57.9	18.2	35.9	3.9	1.8	3.9	3.3	7.0	8.7
	Legume hay	1,336	4,816	22.8	13.1	19.2	9.9	3.1	3.0	0.2	<0.1	0.2	0.1
	Soybeans	984	8,578	25.3	24.1	10.8	13.6	1.0	0.5	1.5	0.6	7.6	5.5
	Winter wheat	662	12,086	15.7	13.9	12.3	10.8	1.2	0.4	0.2	0.1	1.1	1.5
South Central	Corn	671	5,285	54.1	61.0	18.3	18.3	11.0	8.0	11.8	13.3	11.7	20.1
	Cotton	1,505	3,983	40.6	50.2	7.5	9.5	6.5	4.5	16.5	22.2	9.8	13.3
	Rice	3,004	0	77.9	NA	6.9	NA	37.8	NA	24.5	NA	8.6	NA
	Soybeans	3,585	10,498	63.3	63.9	26.0	24.7	10.5	6.8	14.3	18.5	12.1	12.5
	Winter wheat	554	7,341	29.1	32.6	16.9	18.9	3.0	1.8	2.7	2.9	6.3	8.6
Southeast	Cotton	307	2,115	30.0	47.9	6.6	11.3	3.5	1.9	13.6	28.5	5.4	5.6
Southern Great Plains	Corn	1,993	672	50.2	80.9	21.5	56.6	6.4	3.0	2.1	10.9	3.9	8.0
	Cotton	2,831	4,486	36.4	41.3	9.3	17.8	4.6	0.4	4.3	7.8	3.4	2.6
	Legume hay	414	263	23.9	12.1	17.8	11.7	5.8	0.3	0.2	<0.1	<0.1	<0.1
	Peanuts	325	159	60.6	42.8	20.1	11.7	6.8	1.4	19.6	20.9	2.4	2.2
	Sorghum	1,147	3,748	25.9	67.2	10.6	44.5	4.4	1.1	0.6	7.5	2.7	3.2
	Winter wheat	1,991	13,046	26.3	38.6	21.0	33.1	2.0	0.3	0.6	1.5	1.3	2.0
Upper Midwest	Corn	1,517	46,424	47.5	51.8	19.9	23.1	3.3	2.2	12.5	9.2	10.4	16.2
	Soybeans	641	39,409	31.6	32.5	13.0	14.7	1.6	1.4	7.9	4.7	8.5	11.1
West	Barley	601	357	24.3	53.5	3.6	33.6	19.8	3.0	0.1	1.8	0.3	12.4
	Corn silage	297	0	72.2	NA	30.4	NA	29.6	NA	8.8	NA	2.7	NA
	Cotton	1,631	0	55.3	NA	13.0	NA	38.9	NA	2.8	NA	0.4	NA
	Legume hay	1,688	159	20.9	12.3	18.2	8.8	2.4	2.2	0.2	0.1	<0.1	0.9
	Potatoes	329	0	108.9	NA	56.1	NA	38.7	NA	10.0	NA	0.6	NA
	Rice	599	0	23.5	NA	3.9	NA	11.9	NA	6.7	NA	1.0	NA
	Spring wheat	575	197	26.0	39.6	3.8	24.1	20.6	1.1	0.7	0.7	0.4	11.7
	Winter wheat	1,052	1,066	37.1	28.4	19.2	16.5	11.5	0.5	3.2	0.3	2.6	10.6

NA=not applicable
* Irrigated crops with more than 250,000 acres in a region are included in the table. These 26 crop-region combinations represent 92 percent of the irrigated acres included in the study.
** Includes nitrogen loss for all six pathways

Tons of nitrogen loss

Total nitrogen loadings are obtained when the acres of cropland are taken into account. Estimates of the annual tons of nitrogen loss for each of the five principal loss pathways are shown in maps 21–25. Each dot on these five maps represents 500 tons of nitrogen loss from cropland acres to facilitate spatial comparisons of nitrogen loadings.

The Upper Midwest region accounted for about 37 percent of total tons of nitrogen loss (table 35), nearly twice as much as any of the other six regions. The Upper Midwest Region also accounted for 37 percent of the cropland acres included in the study. The percentage of the total nitrogen lost each year was almost exactly the same as the percentage of total cropland acres in three other regions—the Northeast region, the Southern Great Plains region, and the West region (fig. 20). Notably, this occurred in the Upper Midwest and Northeast regions even though the percentages of nitrogen sources were disproportionately high in those regions. Nitrogen losses were disproportionately low in the Northern Great Plains, which is in part be due to the disproportionately low sources of nitrogen inputs (fig. 20). For the South Central and Southeast regions, however, nitrogen losses were disproportionately higher than the proportion of cropland acres.

Tons of nitrogen volatilization losses (map 21) tended to correspond to cropland acres, with some concentration in the Southern Great Plains region (table 35). Tons of nitrogen lost with windborne sediment were concentrated in the Southern Great Plains region (map 22). Over half of the nitrogen lost with waterborne sediment was in the Upper Midwest region (map 3, table 35), with disproportionately low losses in the two Great Plains regions. Nearly 60 percent of the nitrogen loadings for nitrogen dissolved in surface water runoff was in the South Central and Upper Midwest regions, with disproportionately high loadings relative to cropland acres in the West region (map 24, table 35). The Upper Midwest and the South Central regions accounted for the bulk (65%) of nitrogen loadings from nitrogen dissolved in leachate (map 25, table 35), with disproportionately high loadings occurring in the Southeast region.

Corn accounted for the largest share of total nitrogen loss (table 35). Corn acres comprise 26 percent of the cropland acres included in the study. However, corn accounted for 36 percent of the total nitrogen losses, due in part to corn accounting for 50 percent of all commercial fertilizer and manure nitrogen applied (table 38).

Soybeans accounted for the second largest share of nitrogen loss (table 35). In contrast to corn, however, nitrogen loss for soybeans was almost exactly the same proportion as acres of soybeans—23 percent (table 38). Since only 2 percent of the commercial fertilizer and manure nitrogen was applied to soybeans, it is clear that nitrogen from bio-fixation was the primary source of nitrogen loss on soybean acres, and that these losses were directly proportional to the acres of soybeans. Peanuts, the other legume row crop, similarly had disproportionately low commercial fertilizer and manure nitrogen sources relative to acres, but had disproportionately high losses of nitrogen (proportion for nitrogen loss was twice that of acres), probably because of inherent soil and climate characteristics in peanut growing regions. Legume hay, on the other hand, was associated with 24 percent of all nitrogen sources but only accounted for 3.9 percent of nitrogen losses, while accounting for over twice that many acres (legume hay accounted for 8.3 percent of total cropland acres).

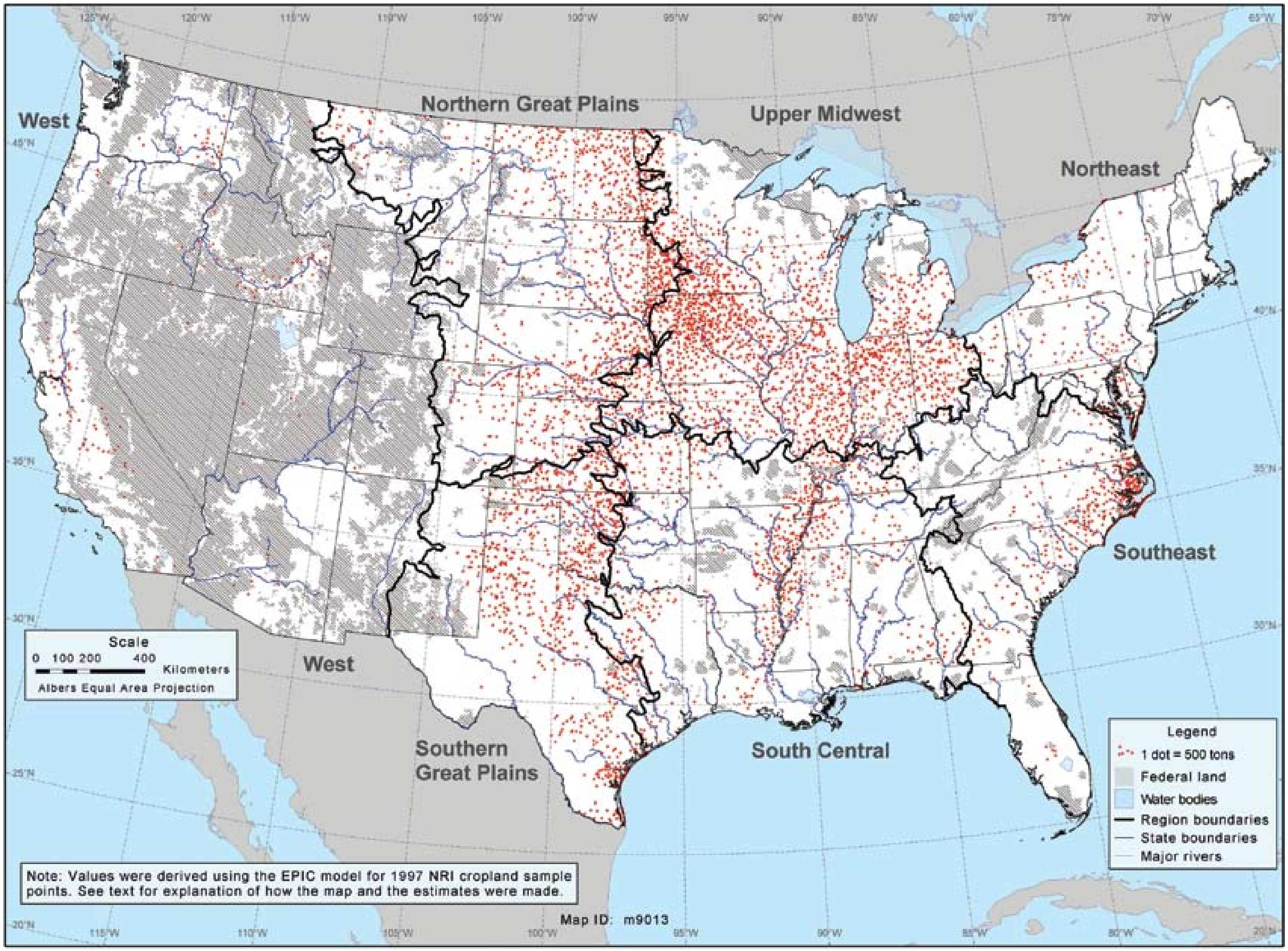
In addition to corn and peanuts, potatoes and rice also had disproportionately high losses of nitrogen, where the proportion of nitrogen loss was nearly twice or more the proportion of acres. Grass hay, spring wheat, oats, and winter wheat had disproportionately low losses of nitrogen relative to acres, in addition to legume hay. For the remaining crops, the shares of total nitrogen loss and acres were closer.

Effects of soil properties on nitrogen loss

Soil properties such as texture and hydrologic soil group explain some of the variability in nitrogen loss results (tables 39 and 40), and also provide opportunities for identifying the most susceptible cropland acres at the local level.

Model simulation results showed that extremely high nitrogen loss occurred on organic soils, averaging over 300 pounds per acre per year (table 39); these soils comprise less than half of one percent of the cropland acres included in the study. The very high levels of organic material in these soils rapidly mineralize when the soil is tilled, releasing significant amounts of nitrogen compounds, a portion of which are subsequently lost to the atmosphere or lost from the field with wind

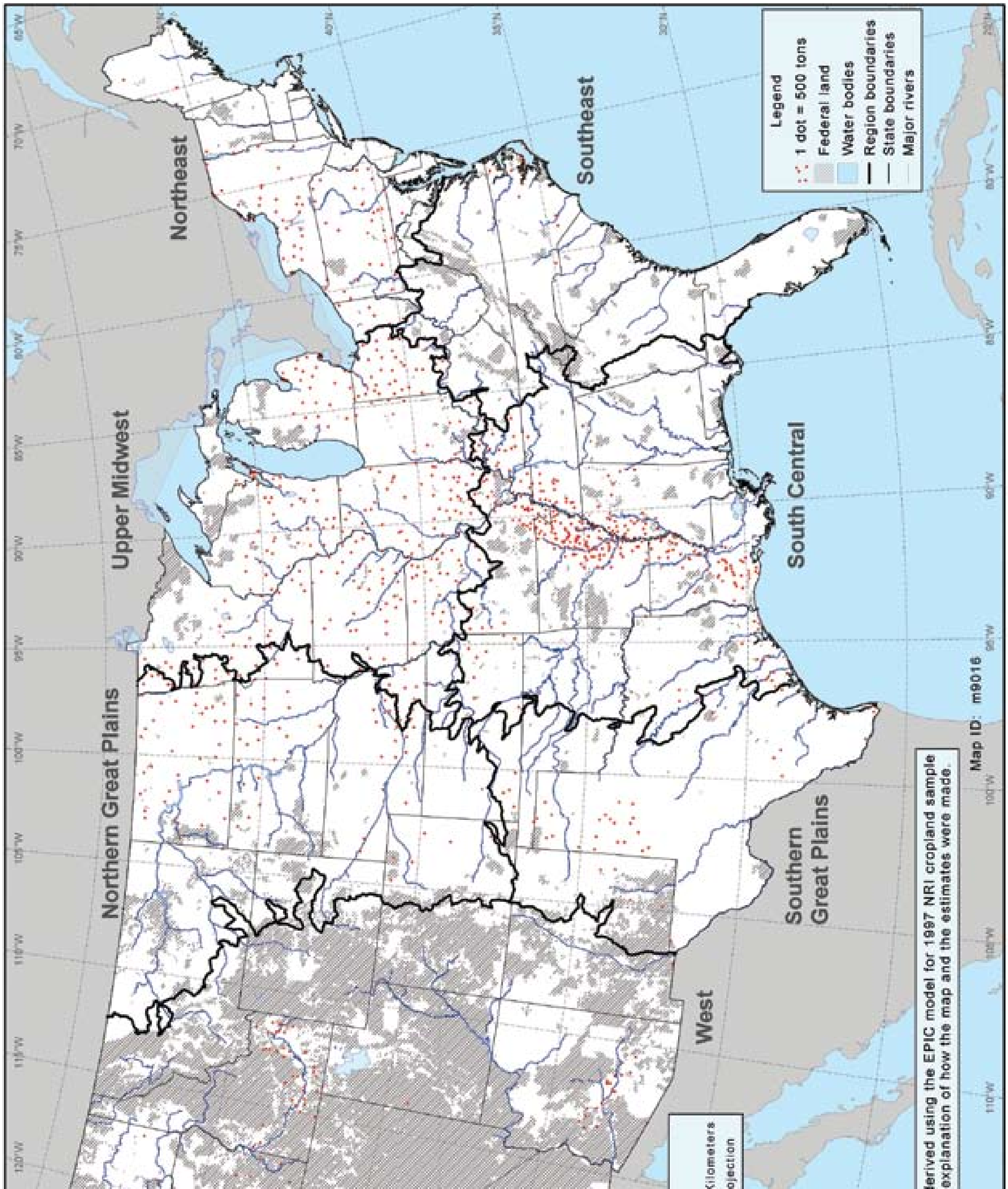
Map 21 Estimated average annual tons of nitrogen lost to the atmosphere



Map 22 Estimated average annual tons of nitrogen lost with windborne sediment

Map 23 Estimated average annual tons of nitrogen lost with waterborne sediment

Map 24 Estimated average annual tons of nitrogen dissolved in surface water runoff



Map 25 Estimated average annual tons of nitrogen dissolved in leachate

Figure 20 Regional percentages of the total for cropland areas, all nitrogen sources, commercial fertilizer and manure nitrogen, and total nitrogen loss

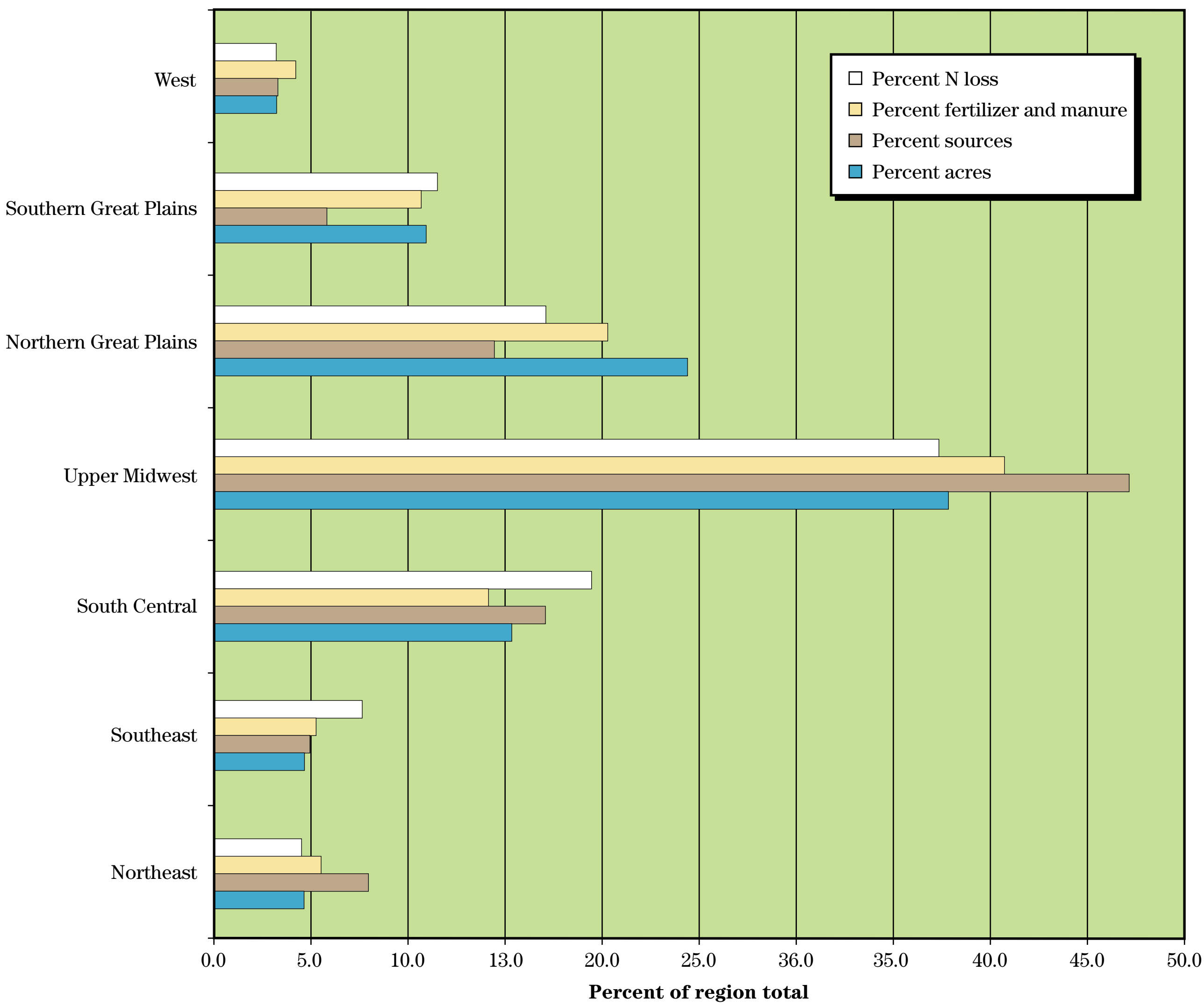


Table 38 Percentages by crop of the total for cropland acres, total nitrogen loss, all nitrogen sources, and commercial fertilizer and manure nitrogen source

Crop	Percent of total cropland acres	Percent of total nitrogen losses	Percent of all nitrogen sources	Percent of commercial fertilizer and manure nitrogen applied
Disproportionately high nitrogen loss relative to acres				
Corn	26.2	36.3	24.5	50.3
Peanuts	0.6	1.2	0.4	0.2
Potatoes	0.3	0.9	0.4	0.8
Rice	1.2	2.1	1.0	1.9
Disproportionately low nitrogen loss relative to acres				
Legume hay	8.3	3.9	24.0	4.7
Grass hay	4.9	2.4	2.8	5.5
S wheat	6.9	3.9	2.2	4.4
W wheat	15.1	11.1	6.2	12.3
Oats	1.3	0.7	0.3	0.5
Nitrogen loss approximately proportional to acres				
Soybeans	22.6	22.8	29.7	2.1
Barley	1.6	1.5	0.9	1.8
Corn silage	1.7	2.5	2.4	5.0
Cotton	5.6	6.3	3.0	5.9
Sorghum	3.7	4.4	2.3	4.7
All crops	100.0	100.0	100.0	100.0

Table 39 Sources of nitrogen applied and estimates of nitrogen loss–by soil texture class (average annual values)

		Nitrogen applied		Nitrogen loss pathways						
Soil texture class	**Percent of cropland acres**	**Commercial fertilizer (lb/a)**	**Manure (lb/a)**	**Lost with waterborne sediment (lb/a)**	**Lost with windborne sediment (lb/a)**	**Volatilized (lb/a)**	**Dissolved in surface water runoff (lb/a)**	**Dissolved in leachate (lb/a)**	**Dissolved in lateral subsurface flow (lb/a)**	**Sum of all losses (lb/a)**
Coarse	5.1	66.0	10.9	1.6	5.7	17.8	2.3	22.7	0.8	50.8
Moderately coarse	10.9	60.1	8.9	3.8	2.5	16.9	3.8	12.4	0.6	40.1
Medium	51.4	58.2	7.6	9.6	1.3	16.2	4.2	4.8	0.4	36.4
Moderately fine	26.2	57.5	6.0	8.9	1.8	19.7	2.8	4.3	0.3	37.9
Fine	6.0	51.1	3.3	10.0	1.2	23.7	6.3	6.9	0.3	48.5
Organic	0.4	71.6	12.7	39.1	0.6	213.8	5.6	49.2	0.3	308.6
Other	<0.1	55.8	13.9	0.7	0.2	14.9	2.6	16.4	0.9	35.7
All	100.0	58.3	7.3	8.5	1.8	18.5	3.8	6.7	0.4	39.7

Table 40 Sources of nitrogen applied and estimates of nitrogen loss–by hydrologic soil group (average annual values)*

		Nitrogen applied		Nitrogen loss pathways						
Hydrologic soil group	**Percent of cropland acres**	**Commercial fertilizer (lb/a)**	**Manure (lb/a)**	**Lost with waterborne sediment (lb/a)**	**Lost with windborne sediment (lb/a)**	**Volatilized (lb/a)**	**Dissolved in surface water runoff (lb/a)**	**Dissolved in leachate (lb/a)**	**Dissolved in lateral subsurface flow (lb/a)**	**Sum of all losses (lb/a)**
A	3.5	65.4	10.4	1.1	6.5	17.4	2.0	22.9	0.8	50.5
B	55.7	58.9	7.8	7.6	2.0	17.6	2.4	6.0	0.5	36.1
C	25.7	57.1	7.4	10.4	0.9	16.3	4.8	5.7	0.4	38.5
D	15.1	55.7	4.0	9.7	1.5	20.5	7.7	6.2	0.2	45.9
All	100.0	58.2	7.2	8.4	1.8	17.7	3.8	6.5	0.4	38.7

* Excludes organic soils

and water erosion. Average application rates for commercial fertilizer and manure were higher on these soils than other soil texture groups (table 39), but not enough to explain the extremely high nitrogen loss rates. Most of the nitrogen loss from organic soils is through volatilization (69%), but high amounts are also lost through leaching and with waterborne sediment. About half of the organic soils are classified as hydrologic soil group A, which has a lower runoff potential and higher infiltration rate than other soil hydrologic groups. Group A soils are found predominately in the Southeast and Upper Midwest regions.

Apart from the high loss rates for organic soils, soil texture and hydrologic soil group had little influence on nitrogen volatilization (tables 39 and 40). Losses were slightly higher for hydrologic soil group D soils when organic soils are excluded.

Nitrogen lost with windborne sediment was strongly influenced by soil texture and hydrologic soil group (tables 39 and 40). Soil texture and hydrologic soil group effects were similar to effects on wind erosion rates shown in figure 12. Highest losses occurred for coarse textured soils and for soils in hydrologic soil group A.

Soil texture and hydrologic soil group also had a pronounced effect on estimates of nitrogen lost with waterborne sediment (tables 39 and 40, fig. 21). Low levels of nitrogen loss occurred on hydrologic soil group A soils, as well as coarse and moderately coarse textured soils. Except for organic soils, the relationship between nitrogen lost with waterborne sediment and soil properties was generally similar to that observed for sediment loss in figure 11.

Loss of nitrogen dissolved in surface water runoff was influenced more by hydrologic soil group than soil texture (fig. 22). Highest losses were for hydrologic soil group D soils, where the average annual loss was about 8 pounds per acre. Hydrologic soil group D soils are the dominant soil type in the South Central region, representing over 40 percent of the cropland acres in that region. Hydrologic soil group A had the lowest loss of nitrogen dissolved in surface water runoff, averaging only 2 pounds per acre per year.

Soil texture played the major role in determining nitrogen dissolved in leachate (fig. 23). Average nitrogen leaching rates were highest for organic soils, followed by coarse textured soils (23 lb/a/yr) and moderately coarse textured soils (12 lb/a/yr). Medium textured soils in hydrologic soil group A also had significant loss, averaging 16 pounds per acre per year. Finer textured soils had average nitrogen leaching losses below 7 pounds per acre per year. This relationship between nitrogen leaching and soil texture reflects the tendency for coarser soil to have larger, more continuous pathways or pores for downward movement of water.

Soil types with the highest nitrogen losses occur less frequently on the landscape than soil types with the lowest nitrogen losses. Organic soils, which had extremely high nitrogen losses in these model simulations, represented less than 0.5 percent of cropland acres. Apart from the organic soils, coarse textured soils had the highest total nitrogen loss (51 lb/a/yr), as did hydrologic group A soils (50 lb/a/yr excluding organic soils). However, these soil groups together comprise only a small fraction of the total cropland acres (<6%). Overall, medium textured soils had the lowest total nitrogen loss rates, averaging 36 pounds per acre per year, and among the hydrologic soil groups, hydrologic soil group B had the lowest total nitrogen loss rates, also averaging 36 pounds per acre per year (tables 39 and 40). Hydrologic soil group B with medium soil texture is the dominant soil type for cropland acres included in the study, representing about 30 percent of cropland acres (table 5).

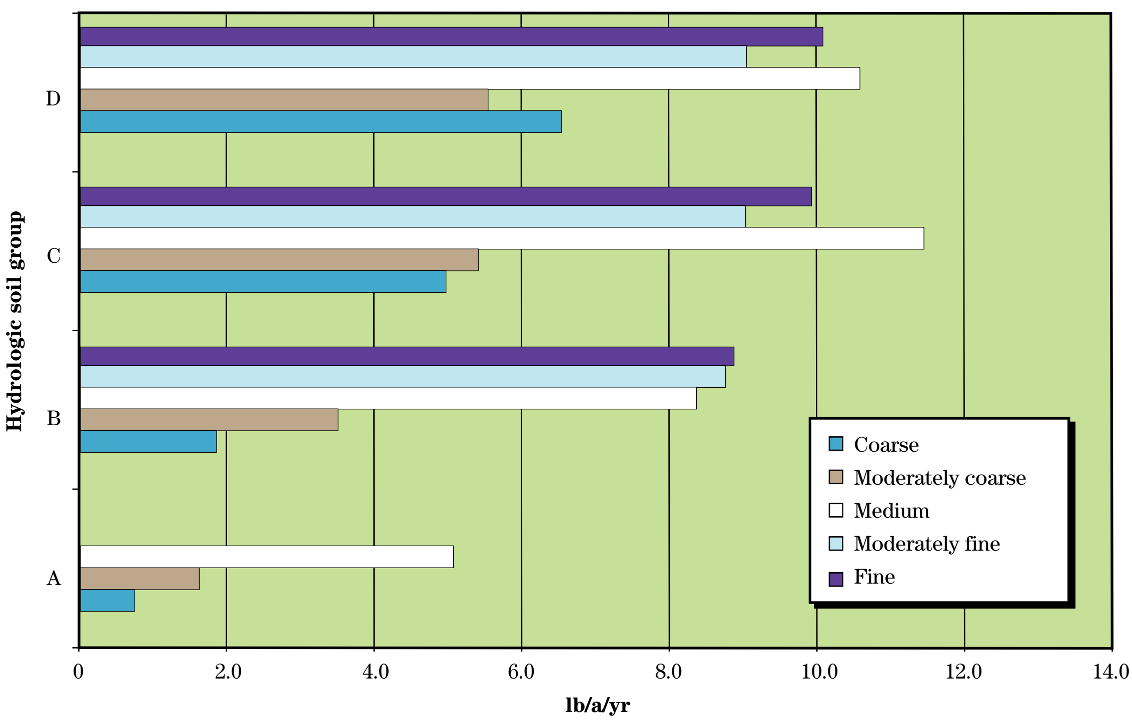
Example of spatial variability of nitrogen loss

Two specific examples of how nitrogen loss varies within a local area are shown in figure 24. The diversity of soil types represented in the model simulations for these two Iowa watersheds was discussed in a previous section (fig. 4). Dominant soils from figure 4 are shown in red in figure 24. Overall, commercial fertilizer and manure nitrogen inputs were about the same in both of these watersheds.

Total nitrogen loss was slightly lower for the Lower Iowa watershed (44.5 lb/a/yr) than for the Floyd watershed (53.1 lb/a/yr). The predominant loss pathway differed between the two watersheds as well; in the Floyd, about half of the nitrogen loss was through volatilization, whereas about half of the losses in the Upper Iowa watershed were with waterborne sediment.

Variability in total nitrogen loss by soil cluster was quite high in both watersheds, ranging from 14 to 113

Figure 21 Average annual loss of nitrogen with waterborne sediment–by hydrologic soil group and soil texture class



Note: Results for organic soils are not shown (see table 26).

Figure 22 Average annual loss of nitrogen dissolved in surface water runoff–by hydrologic soil group and soil texture class

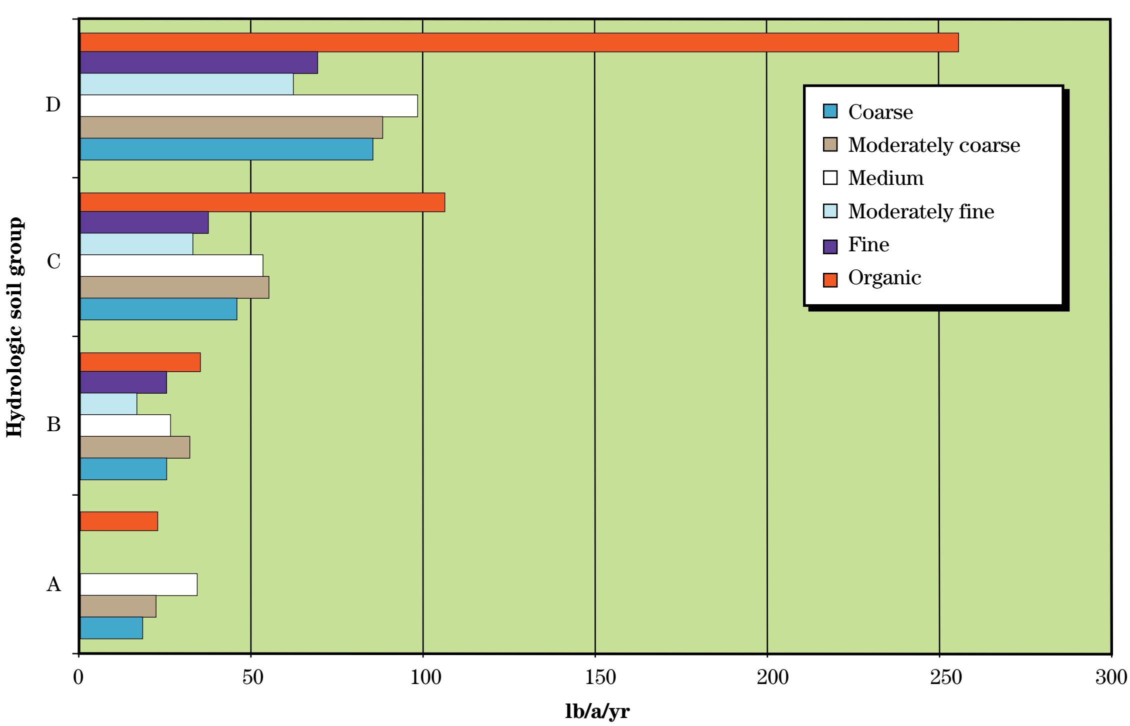


Figure 23 Average annual loss of nitrogen dissolved in leachate–by hydrologic soil group and soil texture class

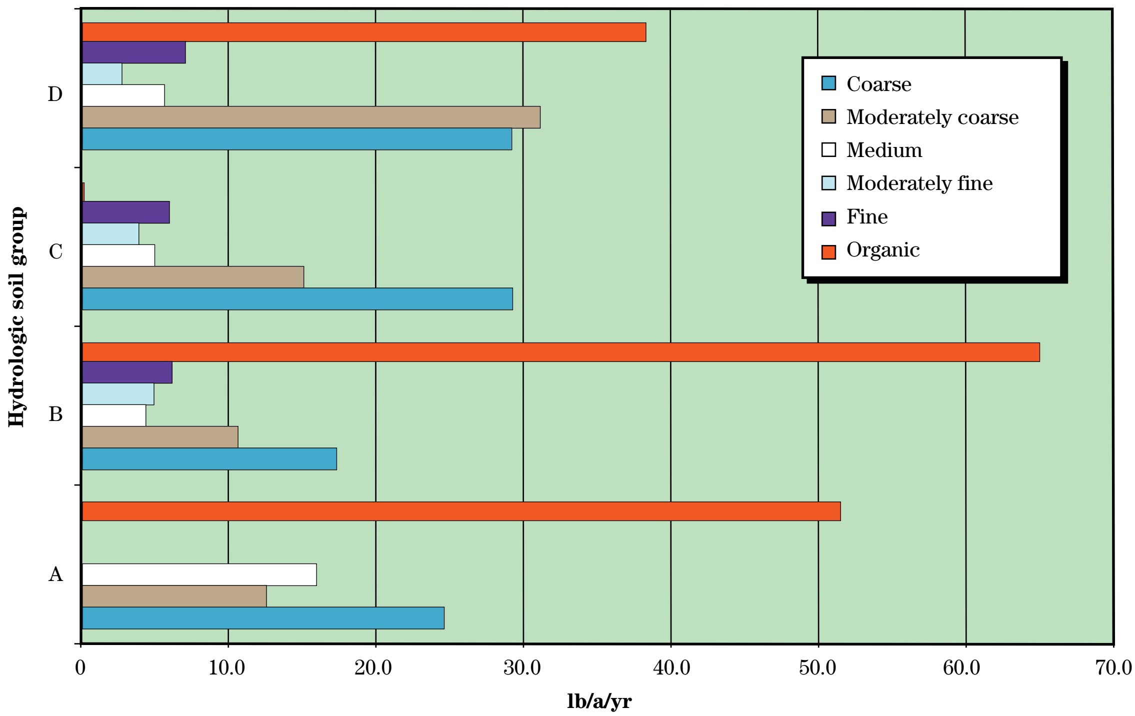
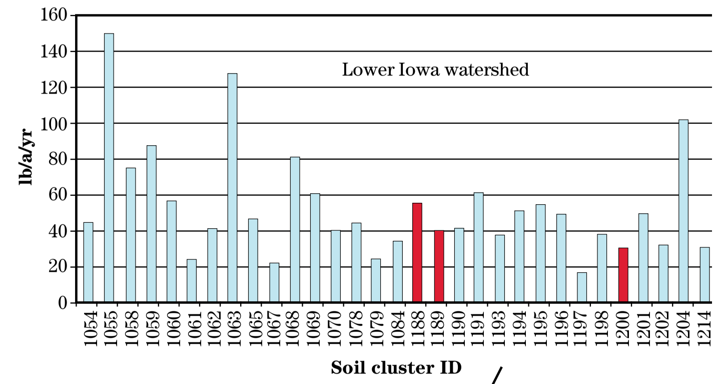
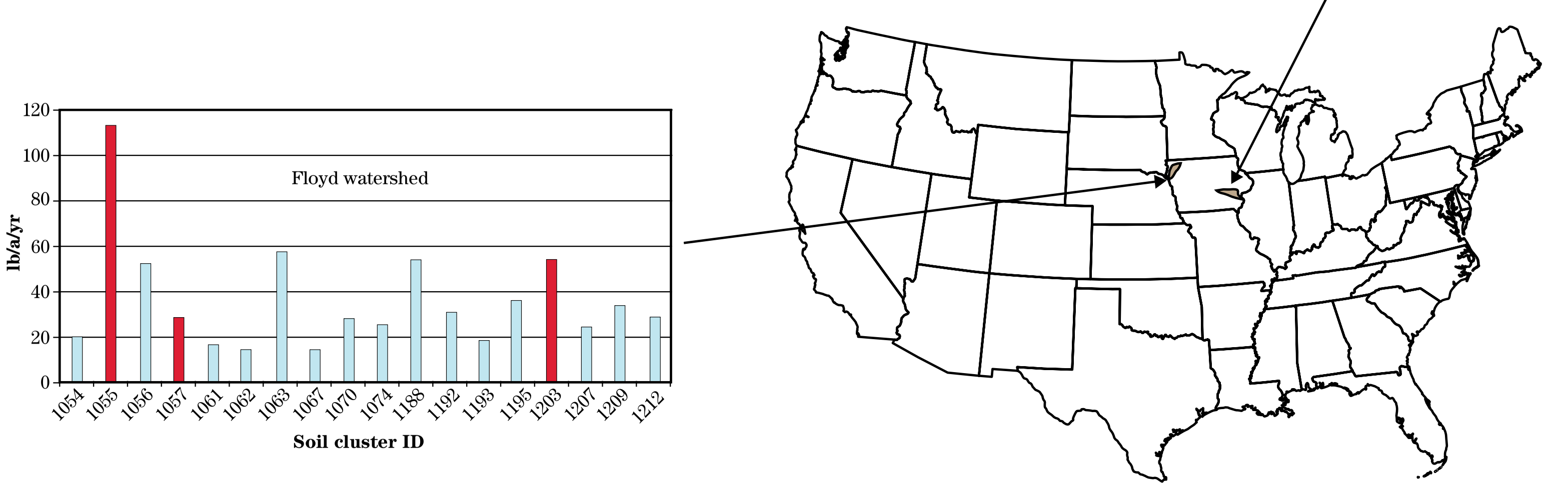


Figure 24 Variability in nitrogen loss estimates (sum of all loss pathways) within two IA watersheds

Soil cluster	Representative soil	Texture group	Hydrologic soil group	Soil cluster	Representative soil	Texture group	Hydrologic soil group
1054	Fairhaven	Medium	B	1189	Lagoda	Medium	B
1055	Kossuth	Moderately fine	B	1190	Sharpsburg	Moderately fine	B
1056	Alton	Moderately fine	C	1191	Adair	Medium	C
1057	Galva	Moderately fine	B	1192	Kenyon	Medium	B
1058	Hoopeston	Moderately coarse	B	1193	Marshall	Moderately fine	B
1059	Coland	Moderately fine	B	1194	Sparta	Coarse	A
1060	Tama	Medium	B	1195	Huntsville	Medium	B
1061	Coppock	Medium	B	1196	Downs	Medium	B
1062	Shelby	Moderately fine	B	1197	Village	Medium	B
1063	Turlin	Medium	B	1198	Lineville	Medium	C
1065	Fayette	Medium	B	1200	Humeston	Medium	C
1067	Nodaway	Medium	B	1201	Lamoni	Fine	C
1068	Gara	Medium	C	1202	Wabash	Moderately fine	D
1069	Lindley	Medium	C	1203	Terril	Medium	B
1070	Colo	Moderately fine	B	1204	Floyd	Medium	B
1074	Ida	Medium	B	1207	Monona	Medium	B
1078	Adair	Moderately fine	C	1209	Racine	Medium	B
1079	Lamont	Moderately coarse	B	1212	Spicer	Moderately fine	B
1084	Dickinson	Moderately coarse	B	1214	Chelsea	Coarse	A
1188	Ely	Medium	B				





pounds per acre in the Floyd watershed and 18 to 150 pounds per acre in the Upper Iowa watershed. In both watersheds, the highest loss occurred for soil cluster 1055 (Kossuth soil), and the second highest loss occurred for soil cluster 1063 (Turlin soil). In the Floyd watershed, about 74 percent of the total nitrogen loss was associated with the 5 soil clusters with the highest loss rates, representing 50 percent of the acres. In the Lower Iowa watershed, the highest losses occurred on soils with few acres—the 8 soil clusters with the highest losses accounted for 16 percent of the total nitrogen loss, but represented only 9 percent of the cropland acres.

Effects of tillage practices on nitrogen loss

Tillage practices were shown to have a significant influence on sediment loss and wind erosion estimates (tables 24 and 30). Model simulations showed that the effect of tillage practices on nitrogen loss estimates was also significant, but not as pronounced as observed for sediment loss. As discussed earlier in this report (table 12 and related discussion), the subset of model runs where all three tillage systems—conventional tillage, mulch tillage, and no-till—were present within a URU was used as the domain for examining the effects of tillage. This tillage comparison subset of model runs included eight crops and represented about 70 percent of the cropland acres covered by the study.

For the 208 million acres in the tillage comparison subset, the tillage-effects baseline nitrogen loss (sum of all loss pathways) averaged 41 pounds per acre per year (table 41), which is nearly the same as the estimate for the full set of NRI sample points included in the study. Model simulation results showed that nitrogen loss summed over all loss pathways would have averaged 44 pounds per acre per year if conventional tillage had been used on all acres, indicating that the tillage practices currently in use have reduced nitrogen loss (sum of all pathways) by 7 percent. As shown for sediment loss, nitrogen loss estimates for mulch tillage were similar to the tillage-effects baseline. Nitrogen loss estimates assuming mulch tillage was used on all acres averaged about 10 percent less than if conventional tillage had been used on all acres. Simulation of full implementation of no-till resulted in an average nitrogen loss of 32 pounds per acre per year, a decrease of nearly 9 pounds per acre, on average, when compared to the tillage-effects baseline. Full implementation of no-till would have the greatest effect in three regions—the Northeast, the Upper Midwest, and the Southern Great Plains regions. The Southeast region, which had the largest estimate of nitrogen loss among the seven regions, would benefit the least in terms of reduced nitrogen loss from additional mulch tillage and only modestly with additional no-till.

The effect of tillage on nitrogen loss estimates varied by crop (table 41). The largest reductions in nitrogen loss for full implementation of mulch tillage compared to the baseline were for barley and spring wheat. Nitrogen loss reductions of about 10 pounds per acre or more, on average, would be obtained for these two crops, as well as three additional crops—corn, corn silage, and sorghum—with full implementation of no-till.

Most of the differences in nitrogen loss among the three tillage systems are for losses that are due to windborne sediment, waterborne sediment, and nitrogen volatilization (fig. 25). In these model simulations, tillage had little effect on soluble nitrogen lost with either surface water runoff or leachate.

Effects of three conservation practices on nitrogen loss

In addition to tillage effects, three conservation practices—contour farming, stripcropping, and terraces—were shown to have a significant influence on nitrogen loss estimates on the basis of the model simulations. As shown for tillage practices, the effect of these three conservation practices on nitrogen loss estimates was modest compared to their effect on sediment loss. For comparison to the results for the model runs that included conservation practices, an additional set of model runs were conducted after adjusting model settings to represent no practices. The difference between the no-practices scenario and the conservation-practices baseline scenario (consisting of the original model runs for NRI sample points with conservation practices) is used here to assess the extent to which conservation practices reduced the nitrogen loss estimates (see table 13 and related discussion).

For the 31.7 million acres modeled with conservation practices, nitrogen loss estimates (sum of all loss pathways) averaged 34 pounds per acre per year (table 42), which was lower than the 40 pounds per acre estimate for the full set of NRI sample points included in the study. Had conservation practices not been accounted for in the model simulations, nitrogen loss estimates on these acres would have averaged 41 pounds

Table 41 Effects of tillage practices on estimates of nitrogen loss, sum of all loss pathways (lb/a/yr)

		Nitrogen loss, all pathways				Change relative to the tillage-effects baseline			Change relative to conventional tillage	
	Acres in tillage comparison subset (1,000s)	Tillage-effects baseline	Conventional tillage	Mulch tillage	No-till	Conventional tillage	Mulch tillage	No-till	Mulch tillage	No-till
By region										
Northeast	6,034	50.4	54.7	49.0	38.3	4.3	-1.4	-12.1	-5.7	-16.4
Northern Great Plains	56,551	82.8	86.6	83.7	77.2	3.8	0.9	-5.6	-2.9	-9.4
South Central	24,879	51.4	54.5	52.5	44.1	3.1	1.1	-7.3	-2.0	-10.4
Southeast	4,442	41.9	45.2	42.2	34.2	3.3	0.3	-7.6	-3.0	-11.0
Southern Great Plains	17,746	28.9	31.9	25.1	19.2	3.0	-3.8	-9.7	-6.8	-12.7
Upper Midwest	96,330	42.6	44.9	38.0	31.9	2.3	-4.6	-10.7	-6.9	-13.0
West	1,661	35.2	39.1	30.7	26.0	4.0	-4.5	-9.1	-8.5	-13.1
By crop										
Barley	3,256	39.5	42.6	28.2	24.0	3.1	-11.3	-15.6	-14.4	-18.7
Corn	71,016	53.7	57.4	53.9	42.2	3.7	0.1	-11.6	-3.5	-15.2
Corn Silage	4,082	55.6	58.2	54.7	42.5	2.6	-0.9	-13.1	-3.5	-15.6
Oats	2,078	21.9	23.9	18.0	15.7	2.0	-3.9	-6.2	-6.0	-8.2
Spring wheat	18,074	21.1	23.7	13.9	11.3	2.6	-7.2	-9.8	-9.9	-12.4
Sorghum	7,697	47.7	50.7	47.3	36.0	2.9	-0.4	-11.8	-3.3	-14.7
Soybeans	62,967	38.1	41.6	39.0	33.0	3.5	0.9	-5.1	-2.6	-8.6
Winter wheat	38,473	27.7	29.8	24.2	21.5	2.1	-3.5	-6.2	-5.6	-8.3
All crops and regions	207,642	40.6	43.8	39.4	32.1	3.2	-1.2	-8.5	-4.4	-11.7

Note: The subset used for this analysis includes only those URUs where all three tillage systems were present. The tillage-effects baseline results represent the mix of tillage systems as reported in the Crop Residue Management Survey for 2000 (CTIC 2001). Tillage-effects baseline results reported in this table will differ from results reported in table 36 because they represent only about 70 percent of the acres in the full database. Results presented for each tillage system represent nitrogen loss estimates as if all acres had been modeled using a single tillage system.

Figure 25 Effects of tillage practices on nitrogen loss estimates–by loss pathway

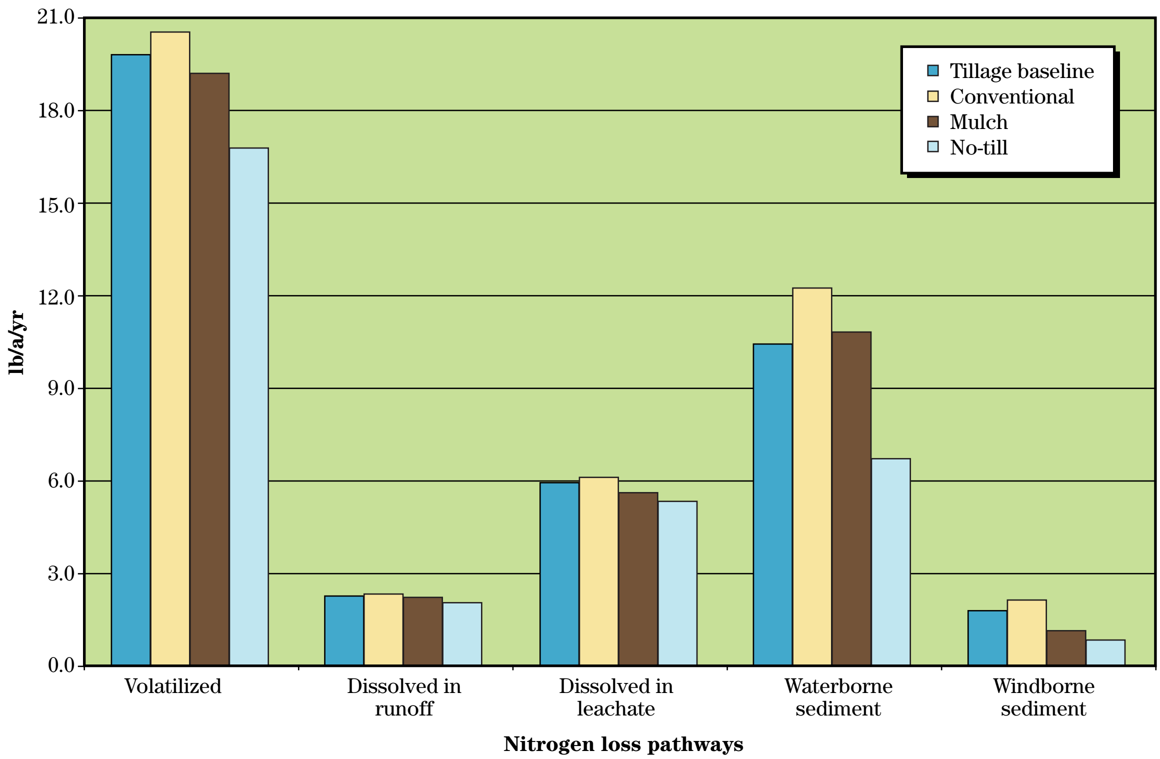


Table 42 Effects of three conservation practices on estimates of nitrogen loss, sum of all loss pathways (lb/a/yr)

				Nitrogen loss			
Region	**Conservation practices**	**Number of NRI sample points**	**Acres (1,000s)**	**Conservation-practices baseline scenario**	**No-practices scenario**	**Difference**	**Percent difference relative to no-practices scenario**
All regions	Contour farming only	3,728	5,965	40.5	50.2	-9.7	-19
	Contour farming and stripcropping	1,183	1,764	28.7	40.3	-11.6	-29
	Contour farming and terraces	7,883	14,728	33.0	40.4	-7.4	-18
	Contour farming, stripcropping, and terraces	31	64	31.0	38.9	-7.9	-20
	Stripcropping only	1,308	2,930	21.0	23.5	-2.5	-11
	Terraces only	3,268	6,285	38.1	40.3	-2.2	-5
	All practices	17,401	31,737	34.1	40.6	-6.6	-16
Northeast	Contour farming only	338	485	46.2	54.7	-8.5	-15
	Contour farming and stripcropping	454	595	36.7	49.7	-13.0	-26
	Stripcropping only	423	526	39.4	49.3	-9.9	-20
	All practices	1,215	1,606	40.4	51.1	-10.6	-21
Southeast	Contour farming only	275	456	51.3	56.2	-4.8	-9
	Contour farming and terraces	132	234	44.9	48.1	-3.1	-7
	Terraces only	52	92	43.0	45.0	-2.0	-5
	All practices	459	782	48.4	52.4	-4.0	-8
South Central	Contour farming only	110	172	58.4	64.5	-6.1	-9
	Contour farming and terraces	1,173	1,963	37.1	43.8	-6.7	-15
	Terraces only	1,169	1,974	36.8	39.2	-2.4	-6
	All practices	2,452	4,109	37.8	42.5	-4.6	-11
Upper Midwest	Contour farming only	2,625	4,239	37.5	49.0	-11.5	-23
	Contour farming and stripcropping	702	1,106	23.9	35.1	-11.3	-32
	Contour farming and terraces	3,621	5,293	31.1	46.6	-15.5	-33
	Stripcropping only	156	231	24.5	30.4	-6.0	-20
	Terraces only	637	985	36.6	42.4	-5.8	-14
	All practices	7,741	11,853	33.1	45.8	-12.7	-28

Table 42 Effects of three conservation practices on estimates of nitrogen loss, sum of all loss pathways (lb/a/yr)—Continued

				Nitrogen loss			
Region	**Conservation practices**	**Number of NRI sample points**	**Acres (1,000s)**	**Conservation-practices baseline scenario**	**No-practices scenario**	**Difference**	**Percent difference relative to no-practices scenario**
Northern Great Plains	Contour farming only	268	365	39.7	44.1	-4.4	-10
	Contour farming and terraces	1,370	3,553	22.7	24.7	-2.0	-8
	Stripcropping only	602	1,945	12.9	13.2	-0.3	-2
	Terraces only	213	495	21.6	22.8	-1.2	-5
	All practices	2,453	6,357	20.6	22.1	-1.5	-7
Southern Great Plains	Contour farming only	104	235	48.4	49.6	-1.2	-2
	Contour farming and terraces	1,585	3,681	42.8	44.2	-1.4	-3
	Stripcropping only	80	149	42.6	42.9	-0.4	-1
	Terraces only	1,122	2,677	42.8	43.7	-0.9	-2
	All practices	2,891	6,743	43.0	44.1	-1.2	-3
West	Terraces only	72	58	27.2	28.5	-1.3	-4

Note: Results for conservation practices and combinations of practices based on less than 20 NRI sample points are not shown in the regional breakdowns, but these data are included in the aggregated results for all regions.

per acre per year, representing a reduction in nitrogen loss of about 7 pounds per acre. These model simulations suggest, therefore, that the conservation practices reported by the NRI reduce nitrogen loss by about 16 percent, on average, for acres with one of more of the three practices.

The bulk of the reductions in nitrogen loss resulted from reductions in waterborne sediment. Volatilization estimates were virtually the same for the two scenarios in all regions, and the practice effects on nitrogen lost with windborne sediment or dissolved in leachate or surface runoff were small in most regions. Estimates of nitrogen dissolved in leachate were typically higher for the baseline scenario than for the no-practices scenario, offsetting some of the overall nitrogen reductions obtained by reducing nitrogen lost with waterborne sediment. This is an expected result; these conservation practices are designed to slow the velocity of surface water runoff, which can lead to more percolation of water into the soil.

The largest reductions occurred for contour farming alone (10 lb/a/yr) and contour farming in combination with stripcropping (12 lb/a/yr). The most prevalent practice set—contour farming and terraces—reduced nitrogen loss estimates about 7 pounds per acre per year, on average. As observed for sediment loss, terraces only or stripcropping only resulted in the smallest reductions in nitrogen loss—about 2 pounds per acre per year on average.

The effects of conservation practices varied considerably by region (table 42). The largest nitrogen loss reductions occurred in the Northeast and Upper Midwest regions, which were also the regions with the highest sediment loss reductions attributable to the three conservation practices. Nitrogen loss reductions for acres with one or more of the three conservation practices in these two regions exceeded 10 pounds per acre per year, on average. The largest reduction in nitrogen loss was for the combination of contour farming and terraces in the Upper Midwest, which reduced nitrogen loss by 16 pounds per acre per year—33 percent.

Implications for reducing nitrogen loss with nutrient management practices

It is not possible to estimate the extent to which nutrient management practices may have reduced nitrogen loss estimates in these model simulations as done in the above sections for tillage practices and conservation practices, mostly because the available databases on nitrogen fertilizer applications did not identify operations that were complying with criteria for Nutrient Management Plans (NMP) and because the model inputs for nitrogen fertilizer were highly aggregated. Nevertheless, some insight into nitrogen loss reductions that may be possible with full implementation of NMP can be obtained by analyzing the results for the various application timing categories and application rate categories used to create the NNLSC database.

A subset of the NNLSC database was analyzed to answer two specific questions:

- If all crop producers adopted application times and rates associated with low nitrogen loss, what is the magnitude of the reduction in nitrogen loss that can be expected?
- What changes in the timing and application rates would be needed to achieve these expected reductions?

The approach taken to address these questions was to select from among the various nutrient management options represented in the database those that minimized nitrogen loss (sum of all loss pathways) for each URU and compare nitrogen loss estimates to those obtained for the full set of nutrient management options. Identifying the low nitrogen loss model runs within each URU guaranteed that all the major soil and climate conditions would be represented in the solution set.

Farmer surveys provided information for commercial fertilizer applications for nine crops included in the EPIC model simulations, representing nutrient management practices for 1990 to 1995 (see earlier section on representing commercial fertilizer applications in the model). A broad range of combinations of nitrogen application timing categories (fall, spring, at plant and after plant, and combinations) and nitrogen application rates (zero, low, medium, high) were simulated.

The scenario domain was restricted to the 9 crops (irrigated and non-irrigated)—corn for grain, soybeans,

sorghum, winter wheat, spring wheat, cotton, rice, peanuts, and potatoes. Model runs with manure applications were excluded because manure application rates used in the model simulations were not obtained from farmer surveys. In addition, URUs with six or fewer nutrient management options were excluded to provide a reasonable amount of diversity among the nutrient management options within each URU. The resulting scenario domain consisted of 586,184 EPIC model runs for 14,699 URUs, representing 236 million cropland acres (about 80% of the full NNLSC database).

Two separate scenarios were constructed: 1) a nitrogen-reduction baseline scenario consisting of the full set of model runs in the domain described above, and 2) a minimum nitrogen loss scenario consisting of a subset of the model runs in the domain.

The minimum nitrogen loss scenario represents aggregate results for only the model runs within each URU that met criteria for minimum nitrogen loss. To select the minimum nitrogen loss nutrient management options, model runs were first grouped together for each tillage system (conventional tillage, mulch tillage, and no-till) within a URU. Separate sets of model runs were selected for each tillage system within a URU to avoid confounding the results with tillage effects. Model runs with crop yields less than 90 percent of the yield obtained for each URU-tillage grouping in the baseline scenario were discarded. This was done to prevent economically infeasible nutrient management options from being selected in the minimum nitrogen loss set. Because the nutrient management options were derived from farmer surveys, all would be expected to be economically feasible; however, some low (or no) nitrogen input options may not have been economically feasible *as modeled*. In some cases, low nitrogen use as reported in farmer surveys would have been associated with manure applications or crop rotations with legume crops in previous years. However, as this information was not available from the survey, some of the model simulations may have resulted in yields that were too low to be economically feasible.

Then, for each tillage subset within a URU, the model run having the lowest total nitrogen loss was identified, as well as all other model runs within that subset with nitrogen losses within 10 percent of the minimum. These model runs were used to represent the minimum nitrogen loss dataset. Application rates and timing categories associated with these model runs were used to define the nutrient management options associated with low nitrogen loss. Approximately 120,000 model runs—20 percent of the scenario domain—met the criteria for inclusion in the minimum nitrogen loss dataset.

Nitrogen loss summed over all loss pathways averaged 43 pounds per acre per year for the nitrogen-reduction baseline scenario, which was close to the 40 pounds per acre estimate for the full set of NRI sample points included in the study (table 43). Nitrogen loss for the minimum nitrogen loss scenario averaged 31 pounds per acre per year, 12 pounds per acre lower than the baseline. This result suggests that if all crop producers adopted application times and rates associated with low nitrogen loss, overall nitrogen loss might be reduced about 30 percent. The largest per-acre reduction in nitrogen loss—26 pounds per acre per year—would occur in the Southeast region, which had the highest per-acre nitrogen leaching loss estimates among the seven regions. The largest percent reduction in nitrogen loss would be expected in the West region, where the minimum nitrogen loss scenario had nitrogen loss estimates 62 percent lower than the baseline scenario. The smallest potential for nitrogen loss reductions occurred in the Upper Midwest and the Northern Great Plains regions. Of the crops included in the analysis, corn consistently showed the greatest potential for nitrogen loss reductions through improved timing of applications and lower application rates (table 43).

Most of the potential for nitrogen loss reductions—80 percent—was due to reductions in nitrogen volatilization and nitrogen dissolved in leachate in these model simulations (table 44). Overall, 52 percent of the potential nitrogen reduction was due to reductions in nitrogen volatilization. Over 75 percent of the potential for nitrogen reduction in the Northern Great Plains and the Southern Great Plains regions was due to reductions in nitrogen volatilization. On average, 28 percent of the potential for nitrogen loss reduction was due to reductions in nitrogen dissolved in leachate. In the Southeast region, about 60 percent of the potential for nitrogen loss reduction was due to reductions in nitrogen dissolved in leachate. This nitrogen loss pathway also accounted for over half of the potential nitrogen loss in the Northeast region. In the West region, the predominate loss pathway associated with potential nitrogen loss was nitrogen dissolved in surface water runoff.

Table 43 Nitrogen loss estimates (sum of all loss pathways) for the nitrogen-reduction baseline scenario and the minimum nitrogen loss scenario (lb/a/yr)

Region	Crop	Acres in baseline scenario (1,000s)	Baseline scenario	Minimum nitrogen loss scenario	Difference	Percent difference relative to baseline scenario
Northeast	All crops	4,250	53.2	37.1	-16.1	-30
Northern Great Plains	All crops	57,302	29.6	20.3	-9.3	-31
South Central	All crops	37,813	54.7	42.1	-12.7	-23
Southeast	All crops	9,191	81.7	55.6	-26.1	-32
Southern Great Plains	All crops	29,702	43.9	23.1	-20.8	-47
Upper Midwest	All crops	94,174	42	32.2	-9.9	-24
West	All crops	3,586	51.9	19.9	-32	-62
All regions	All crops	236,019	43.2	30.6	-12.6	-29
By crop within region*						
Northeast	Corn	2,889	54.2	34.4	-19.8	-37
	Soybeans	1,146	42.8	37.2	-5.6	-13
Northern Great Plains	Corn	15,425	52	31.6	-20.4	-39
	Spring wheat	18,720	22.1	15.4	-6.7	-30
	Sorghum	1,460	45.9	23.7	-22.2	-48
	Soybeans	9,351	24.2	23.6	-0.6	-2
	Winter wheat	12,156	13.9	10.1	-3.8	-27
South Central	Corn	5,899	60.8	32.5	-28.4	-47
	Cotton	5,487	47.6	28.2	-19.3	-41
	Peanuts	864	77.7	69.4	-8.4	-11
	Rice	3,004	77.9	49	-28.9	-37
	Sorghum	2,585	43.5	24.4	-19.1	-44
	Soybeans	12,607	63.1	61.7	-1.4	-2
	Winter wheat	7,367	32.7	26.5	-6.2	-19
Southeast	Corn	2,934	116.3	56.7	-59.5	-51
	Cotton	2,422	45.7	30.3	-15.4	-34
	Peanuts	470	81.1	71.2	-9.9	-12
	Soybeans	2,344	78.5	73.9	-4.6	-6
	Winter wheat	1,021	75.6	63.5	-12.1	-16
Southern Great Plains	Corn	2,645	64.3	27.2	-37.1	-58
	Cotton	7,306	39.5	25	-14.5	-37
	Peanuts	465	54.3	37.3	-17	-31
	Sorghum	4,497	59.5	23.9	-35.6	-60
	Winter wheat	14,767	37.4	20.8	-16.6	-44

Table 43 Nitrogen loss estimates (sum of all loss pathways) for the nitrogen-reduction baseline scenario and the minimum nitrogen loss scenario (lb/a/yr)—Continued

Region	Crop	Acres in baseline scenario (1,000s)	Baseline scenario	Minimum nitrogen loss scenario	Difference	Percent difference relative to baseline scenario
Upper Midwest	Corn	47,394	51.6	33.4	-18.2	-35
	Spring wheat	815	29.5	21.1	-8.4	-28
	Sorghum	1,471	33.8	21.9	-11.9	-35
	Soybeans	39,649	32.4	32	-0.4	-1
	Winter wheat	4,720	28	25.8	-2.1	-8
West	Cotton	1,631	52	10.6	-41.4	-80
	Potatoes	323	109.5	42.8	-66.7	-61
	Winter wheat	1,435	32.5	21.8	-10.7	-33

Note: Results for crops within regions with less than 250,000 acres are not shown, but these data are included in the aggregated results by region.

Table 44 Nitrogen loss reductions (nitrogen loss estimates for the nitrogen-reduction baseline scenario minus the minimum nitrogen loss scenario) for each nitrogen loss pathway (lb/a/yr)

Region	Dissolved in surface water runoff	Dissolved in leachate	Dissolved in lateral subsurface flow	Volatilization	Lost with waterborne sediment	Lost with windborne sediment	Sum of all loss pathways
Northeast	0.89	8.56	0.43	3.53	2.67	0.06	16.1
Northern Great Plains	0.67	0.74	0.17	7.05	0.30	0.33	9.3
South Central	2.18	5.45	0.13	3.59	1.26	0.08	12.7
Southeast	0.99	15.59	0.28	8.23	1.00	0.00	26.1
Southern Great Plains	0.91	2.85	0.16	15.75	0.24	0.87	20.8
Upper Midwest	0.50	3.48	0.16	4.36	1.30	0.06	9.9
West	19.47	1.92	0.22	10.26	0.11	0.03	32.0
All regions	1.18	3.59	0.17	6.55	0.91	0.23	12.6

What changes in the timing and application rates would be needed to achieve these expected reductions? In this analysis, the potential for nitrogen loss reduction was determined by the set of model runs associated with low nitrogen loss. This set of model runs represented a different mix of application rate categories and application timing categories than in the baseline scenario. The difference in the mix between the two scenarios is an indication of some of the changes in current nutrient management practices that would be necessary to realize the potential for nitrogen loss reductions reported.

The mix of application rate and timing categories for the two scenarios can be represented by the proportion of model runs in each category (table 45). Comparing the mix of application rate and timing categories in the two scenarios indicates that nitrogen loss reductions could be achieved by:

- Reducing the nitrogen application rates for producers with rates in the top third (the high rate category) to rates similar to the lower rates used by the other two-thirds of producers. In the minimum nitrogen loss scenario, only 6 percent of the model runs had application rates in the high rate category and 44 percent had application rates in the low rate category, whereas in the baseline scenario the three application rate categories were about equally represented.
- Reducing the occurrence of fall applications of nitrogen wherever possible. In the baseline scenario, 37 percent of the model runs included a fall application, compared to only 24 percent for the minimum nitrogen loss scenario.

Table 45 Percentage of model runs in each application rate and timing category for the nitrogen-reduction baseline scenario and the minimum nitrogen loss scenario

Category	Percent of model runs in the minimum nitrogen loss scenario	Percent of model runs in the baseline scenario
Application rate categories*		
High nitrogen rates	6.7	31.2
Medium nitrogen rates	32.5	32.5
Low nitrogen rates	44.0	30.7
No nitrogen applications	16.8	5.7
All categories	100.0	100.0
Application timing categories**		
Spring before plant only	22.8	20.8
At plant only	22.5	11.1
After plant only	17.5	12.9
Fall only	18.1	22.7
Fall and spring	0.2	2.6
Fall and at plant	1.1	4.7
Fall and after plant	4.2	7.3
Spring and at plant	2.6	6.8
Spring and after plant	3.2	4.3
At plant and after plant	7.6	6.8
All categories	100.0	100.0

* High, medium, and low application rate categories were derived from the farmer surveys and represent different rates for each crop and state. The high category is based on the highest third of the application rates in the survey sample and the low category is based on the lowest third of the application rates in the survey sample for each crop and state (see section on representing commercial fertilizer applications in the model).

** Excludes occurrences of no nitrogen applications

- Replacing fall applications with applications at plant or applications after plant. In the minimum nitrogen loss scenario, 40 percent of the model runs were for applications either at plant or after plant, compared to 24 percent for the baseline scenario.
- Reducing the occurrence of nitrogen applications in multiple time periods. In the minimum nitrogen loss scenario, 81 percent of the model runs were for applications in only one time period, compared to 67 percent for the baseline scenario.

Assessment of critical acres for nitrogen loss

Three of the six nitrogen loss pathways are used to identify critical acres for nitrogen loss:

- nitrogen lost with waterborne sediment
- nitrogen dissolved in surface water runoff
- nitrogen dissolved in leachate

Nitrogen loss from volatilization was not used to identify critical acres because loss estimates were high for nearly all cropland acres; identification of the highest subsets tends to reinforce critical acres identified by other measures rather than define additional acres with resource concerns. Nitrogen lost with windborne sediment is well represented by critical acres identified for wind erosion. Nitrogen loss dissolved in lateral subsurface flow had levels too low to be useful as a criterion for identifying critical acres.

Specific regions of the country have been shown in this study to have a much higher potential for nitrogen loss from one of these three nitrogen loss pathways than other areas of the country. Moreover, as shown in maps 17, 19, and 20 and in the example for the two Iowa watersheds, nitrogen loss estimates often varied considerably within relatively small geographic areas. Estimates of the average nitrogen loss by region and by crops within regions mask much of this underlying variability. Tables 46 through 48 demonstrate the extent of both regional and local variability by presenting the percentiles for each of the three nitrogen loss pathways for each region.

For nitrogen lost with waterborne sediment, the mean of the distribution exceeded the median for all regions (table 46), indicating that the bulk of the nitrogen loss estimates for this pathway is below the average and that there is a minority of sample points with very high loss estimates. This disproportionality was pronounced for three regions—the Northeast, the Southeast, and the West. For all regions, loss estimates for acres at or above the 90th percentile threshold were over twice the average. In the Southeast and the West, the mean was nearly the same as or exceeded the 75th percentile.

All regions exhibited strong disproportionality for nitrogen dissolved in leachate and dissolved in surface water runoff (tables 47 and 48). The mean for nitrogen dissolved in surface water runoff (3.8 lb/a/yr) was over twice that of the 50th percentile (1.7 lb/a/yr) for all acres included in the study. The mean for nitrogen dissolved in leachate (6.7 lb/a/yr) was over six times that of the 50th percentile (1.1 lb/a/yr) and exceeded the 75th percentile for all cropland acres included in the study.

Five categories of critical acres for nitrogen lost with waterborne sediment, representing different degrees of severity, are defined on the basis of national level results:

- acres where per-acre nitrogen loss is above the 95th percentile for all acres included in the study (26.597 lb/a/yr)
- acres where per-acre nitrogen loss is above the 90th percentile for all acres included in the study (19.425 lb/a/yr)
- acres where per-acre nitrogen loss is above the 85th percentile for all acres included in the study (16.181 lb/a/yr)
- acres where per-acre nitrogen loss is above the 80th percentile for all acres included in the study (13.518 lb/a/yr)
- acres where per-acre nitrogen loss is above the 75th percentile for all acres included in the study (11.733 lb/a/yr)

Five categories of critical acres for nitrogen dissolved in surface water runoff were defined in a similar manner:

- acres where per-acre nitrogen loss is above the 95th percentile for all acres included in the study (12.863 lb/a/yr)

Table 46 Percentiles of nitrogen lost with waterborne sediment (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	13.362	0.000	0.000	0.100	4.604	20.742	38.225	52.145
Northern Great Plains	72,396,500	36,035	4.543	0.020	0.189	1.029	4.143	6.453	9.124	12.974
South Central	45,349,900	27,465	10.935	0.059	0.810	5.054	9.122	14.346	21.351	27.629
Southeast	13,394,400	8,955	7.108	0.025	0.072	0.518	2.978	7.265	16.176	24.177
Southern Great Plains	32,096,000	14,495	2.555	0.082	0.350	0.804	1.965	3.492	5.618	7.475
Upper Midwest	112,580,900	74,691	11.816	0.013	0.221	5.007	9.658	16.144	24.649	32.286
West	9,018,400	5,644	2.726	0.000	0.000	0.036	0.306	1.147	10.168	14.110
All regions	298,478,000	178,567	8.507	0.014	0.116	1.597	5.773	11.733	19.425	26.597

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.

Table 47 Percentiles of nitrogen dissolved in surface water runoff (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	6.638	1.096	1.429	2.534	5.276	8.687	14.344	16.403
Northern Great Plains	72,396,500	36,035	1.794	0.094	0.168	0.396	1.008	2.425	4.357	5.641
South Central	45,349,900	27,465	7.700	0.581	0.947	2.352	5.103	9.450	13.736	31.077
Southeast	13,394,400	8,955	3.970	0.259	0.585	1.312	2.716	5.553	9.076	11.345
Southern Great Plains	32,096,000	14,495	1.706	0.047	0.093	0.161	0.515	2.348	4.848	6.906
Upper Midwest	112,580,900	74,691	2.834	0.586	0.671	0.957	1.489	3.126	7.530	9.341
West	9,018,400	5,644	15.973	0.168	0.280	1.715	11.037	25.750	44.273	50.443
All regions	298,478,000	178,567	3.822	0.149	0.327	0.802	1.721	4.396	8.961	12.863

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.

Table 48 Percentiles of nitrogen dissolved in leachate (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	6.811	0.053	0.094	0.306	1.599	8.783	18.757	24.755
Northern Great Plains	72,396,500	36,035	1.018	0.000	0.000	0.000	0.000	0.149	2.115	6.256
South Central	45,349,900	27,465	13.417	0.061	0.150	1.447	8.142	19.231	34.986	46.239
Southeast	13,394,400	8,955	29.907	0.039	0.106	1.510	16.393	36.588	59.228	78.240
Southern Great Plains	32,096,000	14,495	3.826	0.000	0.000	0.045	0.681	3.356	11.710	20.150
Upper Midwest	112,580,900	74,691	6.025	0.016	0.075	0.518	1.965	5.485	15.391	25.881
West	9,018,400	5,644	2.284	0.000	0.000	0.001	0.085	0.628	4.188	7.825
All regions	298,478,000	178,567	6.692	0.000	0.000	0.051	1.094	6.069	18.902	31.454

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.

- acres where per-acre nitrogen loss is above the 90th percentile for all acres included in the study (8.961 lb/a/yr)
- acres where per-acre nitrogen loss is above the 85th percentile for all acres included in the study (7.046 lb/a/yr)
- acres where per-acre nitrogen loss is above the 80th percentile for all acres included in the study (5.413 lb/a/yr)
- acres where per-acre nitrogen loss is above the 75th percentile for all acres included in the study (4.396 lb/a/yr)

Five categories of critical acres for nitrogen dissolved in leachate were defined in a similar manner:

- acres where per-acre nitrogen loss is above the 95th percentile for all acres included in the study (31.454 lb/a/yr)
- acres where per-acre nitrogen loss is above the 90th percentile for all acres included in the study (18.902 lb/a/yr)
- acres where per-acre nitrogen loss is above the 85th percentile for all acres included in the study (12.674 lb/a/yr)
- acres where per-acre nitrogen loss is above the 80th percentile for all acres included in the study (8.659 lb/a/yr)
- acres where per-acre nitrogen loss is above the 75th percentile for all acres included in the study (6.069 lb/a/yr)

The regional representation of critical acres is shown in tables 49–51 for each of the five categories. About 95 percent of the acres with per-acre estimates of nitrogen lost with waterborne sediment in the top 5 percent were in three regions—the Upper Midwest region (60% of critical acres), the South Central region (17% of critical acres), and the Northeast region (17% of critical acres). These are the same three regions with most of the critical acres for sediment loss.

For nitrogen dissolved in surface water runoff, the South Central (34%) and West (28%) regions had the majority of acres in the top 5 percent. As the criterion for critical acres expanded from the top 5 percent to the top 25 percent, the Upper Midwest replaced the West as the region with the second highest number of critical acres for nitrogen dissolved in surface water runoff.

For nitrogen dissolved in leachate, three regions had about 90 percent of the critical acres in the top 5 percent category—the South Central region (37%), the Southeast (27%) and the Upper Midwest (26%). In the Northeast region, over half of the cropland acres were designated as critical acres in the top 25 percent nationally for nitrogen dissolved in surface water runoff. In the South Central region, over half of the cropland acres were designated as critical acres in the top 25 percent nationally for both nitrogen dissolved in surface water runoff and nitrogen dissolved in leachate. In the Southeast region, two-thirds of the cropland acres were critical acres in the top 25 percent nationally for nitrogen dissolved in leachate.

These critical acres accounted for the bulk of the 570,341 tons per year of nitrogen dissolved in surface water runoff, 998,637 tons per year of nitrogen dissolved in leachate, and the 1,269,517 tons per year of nitrogen lost with waterborne sediment. The 95th percentile category, representing the 5 percent of acres with the highest per-acre losses, accounted for 32 percent of the total tons of nitrogen dissolved in surface water runoff, 44 percent of the total tons of nitrogen dissolved in leachate, and 23 percent of the total tons of nitrogen lost with waterborne sediment. The 25 percent of acres with the highest per-acre losses accounted for 71 percent of the total tons of nitrogen dissolved in surface water runoff, 87 percent of the total tons of nitrogen dissolved in leachate, and 63 percent of the total tons of nitrogen lost with waterborne sediment.

Percentile	Percent of total tons of nitrogen dissolved in leachate	Percent of total tons of nitrogen dissolved in surface water runoff	Percent of total tons of nitrogen lost with waterborne sediment
95th	44.3	32.4	23.3
90th	62.5	46.3	36.7
85th	74.1	56.7	47.0
80th	81.9	64.8	55.7
75th	87.4	71.2	63.1

Table 49 Critical areas for nitrogen lost with waterborne sediment

Region	Acres	Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 25% nationally	
		Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Northeast	13,641,900	2,593,100	17.4	3,556,000	11.9	4,142,600	9.3	4,712,700	7.9	5,079,100	6.8
Northern Great Plains	72,396,500	71,600	0.5	359,500	1.2	1,966,500	4.4	3,253,400	5.4	4,087,900	5.5
South Central	45,349,900	2,562,200	17.2	5,976,300	20.0	8,858,100	19.8	12,843,200	21.5	16,342,900	21.9
Southeast	13,394,400	593,200	4.0	1,047,900	3.5	1,331,600	3.0	1,625,300	2.7	2,100,900	2.8
Southern Great Plains	32,096,000	0	0.0	0	0.0	62,700	0.1	212,200	0.4	293,300	0.4
Upper Midwest	112,580,900	8,940,800	59.9	18,626,700	62.4	28,068,500	62.7	36,606,200	61.3	46,082,500	61.7
West	9,018,400	153,200	1.0	289,900	1.0	342,000	0.8	467,600	0.8	643,000	0.9
All regions	298,478,000	14,914,100	100.0	29,856,300	100.0	44,772,000	100.0	59,720,600	100.0	74,629,600	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 46. Other columns correspond to table 46 in a similar manner.

Table 50 Critical areas for nitrogen dissolved in surface water runoff

Region	Acres	Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 25% nationally	
		Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent	Acres	Percent
Northeast	13,641,900	1,977,100	13.2	3,259,000	10.9	4,599,900	10.3	6,622,900	11.1	8,076,400	10.8
Northern Great Plains	72,396,500	270,800	1.8	985,600	3.3	2,142,900	4.8	3,967,600	6.6	7,118,200	9.5
South Central	45,349,900	5,090,100	34.1	12,005,100	40.3	16,726,900	37.4	21,835,300	36.6	25,260,500	33.9
Southeast	13,394,400	363,900	2.4	1,377,200	4.6	2,195,600	4.9	3,417,300	5.7	4,394,600	5.9
Southern Great Plains	32,096,000	302,100	2.0	625,300	2.1	1,556,100	3.5	2,545,900	4.3	3,756,500	5.0
Upper Midwest	112,580,900	2,673,300	17.9	6,733,700	22.6	12,512,300	28.0	16,022,200	26.8	20,485,500	27.5
West	9,018,400	4,247,100	28.5	4,796,400	16.1	5,014,700	11.2	5,277,700	8.8	5,516,200	7.4
All regions	298,478,000	14,924,400	100.0	29,782,300	100.0	44,748,400	100.0	59,688,900	100.0	74,607,900	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 47. Other columns correspond to table 47 in a similar manner.

Table 51 Critical areas for nitrogen dissolved in leachate

		Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 25% nationally	
Region	**Acres**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**
Northeast	13,641,900	450,400	3.0	1,360,000	4.6	2,200,700	4.9	3,498,200	5.9	4,358,800	5.8
Northern Great Plains	72,396,500	301,900	2.0	619,000	2.1	1,292,400	2.9	2,143,300	3.6	3,710,600	5.0
South Central	45,349,900	5,495,400	36.8	11,547,500	38.7	16,521,200	36.9	21,766,800	36.5	25,460,800	34.1
Southeast	13,394,400	4,030,100	27.0	6,057,500	20.3	7,584,200	16.9	8,240,600	13.8	8,824,200	11.8
Southern Great Plains	32,096,000	577,500	3.9	1,779,600	6.0	3,026,800	6.8	4,778,400	8.0	5,521,200	7.4
Upper Midwest	112,580,900	3,899,600	26.1	8,252,000	27.7	13,816,000	30.9	18,858,400	31.6	26,025,500	34.9
West	9,018,400	171,300	1.1	227,200	0.8	329,200	0.7	409,100	0.7	716,100	1.0
All regions	298,478,000	14,926,200	100.0	29,842,800	100.0	44,770,500	100.0	59,694,800	100.0	74,617,200	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 48. Other columns correspond to table 48 in a similar manner.

Phosphorus loss

Modeling the phosphorus cycle

Phosphorus, like nitrogen, is an essential element needed for crop growth. It is a basic building block for compounds that store and transfer energy, nucleic acids, and other organic compounds. Unlike nitrogen, phosphorus is not found in a gaseous form, and so the cycle does not have an atmospheric component. It is most commonly found in rock formations and sediments as phosphate salts. It is also found as part of the organic material in soil. Weathering processes dissolve the phosphates, and plants uptake phosphorus from the soil water in the form of hydrated phosphate ions—soluble phosphorus. Phosphorus is released back to the soil as crop residue decomposes, and the cycle repeats. Phosphates are not very water-soluble, and quantities of soluble phosphorus in soil are generally small, ranging from 0.2 to 0.3 milligrams per liter.

Farmers apply commercial phosphorus fertilizers to supplement the usually low quantities available in the soil. Over-application can lead to the buildup of phosphorus in the soil. As the phosphorus levels build up in the soil, the potential for phosphorus in a soluble form increases (Sharpley et al. 1999). Dissolved phosphorus that is transported from farm fields to lakes, rivers, and streams can lead to excessive aquatic plant growth, resulting in eutrophication. Phosphorus is sometimes the limiting factor for biomass production in freshwater ecosystems; even small amounts (concentrations as low as 0.02 mg/L) added to the system can produce significant increases in plant and algal growth (Sharpley et al. 1999).

Generally, the factors that cause phosphorus movement are similar as those that cause nitrogen movement. Transport mechanisms are erosion, surface water runoff from rainfall and irrigation, and leaching. Factors that influence the source and amount of phosphorus available to be transported are soil properties, and the rate, form, timing, and method of phosphorus applied. The phosphate ion attaches strongly to soil particles and makes up a part of soil organic particles. Any erosion of these particles will transport phosphorus from the site. Phosphorus can also be transported as soluble material in runoff and leaching water. When water moves over the soil surface, as it does in runoff events, or passes through the soil profile during leaching, soluble phosphorus will be transported with the water. Applying phosphorus fertilizer or manures on the soil surface will subject them to both runoff and erosion, particularly if the application takes place just before a rainfall, irrigation, or wind event that can carry the phosphorus material off site. If, however, the fertilizer or manure material is incorporated into the soil profile, it becomes protected from the transport mechanisms of wind and water. Leaching of phosphorus is at a higher risk through coarse textured soils or organic soils that have low clay content.

Phosphorus is primarily lost from farm fields through three processes: attached to the sediment that erodes from the field, dissolved in the surface water runoff, or dissolved in leachate and carried through the soil profile. On cultivated fields, most is lost through erosion, whereas on non-tilled fields most phosphorus losses are dissolved in surface water runoff or in leachate. Cultivated acres with phosphorus-rich soils, however, can also lose significant amounts of phosphorus dissolved in the runoff or the leachate.

EPIC simulates the phosphorus cycle as shown in figure 26. EPIC simulates mineral and organic fractions of soil phosphorus. The mineral fraction consists of available (soluble), active (loosely labile), and stable (fixed) pools. Only phosphorus compounds that are soluble in water are available for plants to use. The soluble and active pools are assumed to be in rapid equilibrium (several days or weeks). The soluble pool is input and the size of the active and stable pools relative to the soluble pool is set by EPIC based on the amount of past soil weathering. The active pool is in slow equilibrium with the stable pool. Fertilizer phosphorus is assumed to be in soluble form which is mixed uniformly to a specific depth. Thus, fertilizer phosphorus contributes directly to the soluble pool. Organic phosphorus is divided into the fresh residue pool, consisting of phosphorus in the microbial biomass, manures, and crop residues, and the active and stable humus pools. Humic mineralization occurs in the active pool only. The model accounts for transformations between pools within each fraction and also between the organic and mineral fractions. Plant use of phosphorus is estimated using the supply and demand approach, which balances soluble phosphorus in the soil with an ideal phosphorus concentration in the plant for a given day.

Phosphorus in the surface layer is partitioned into adsorbed and solution phases using a constant partition coefficient similar to the method described by Leonard and Wauchope (1980). Adsorbed phosphorus attaches to soil particles in the soil matrix, thereby removing the material from solution. Sediment transport of phosphorus is simulated with a loading function similar to that used for organic nitrogen transport. The amount of soluble phosphorus removed in surface water runoff is predicted using soluble phosphorus concentration in the top 10 millimeters of soil, runoff volume, and partition coefficient. A similar method is used to predict soluble phosphorus lost with percolation water as leachate. Part of the phosphorus is removed from the field with the harvested crop and remaining crop residue is added into the organic pools where it is available for mineralization. Transformations of organic phosphorus in crop residues and soil organic matter are similar to the transformations of crop residues, soil organic matter, and organic nitrogen in the PAPRAN model (Seligman and Keulen 1981).

Over years of farming, cropland soils tend to either gain or lose phosphorus. In cases where soils experience net losses (mining), reductions in soil quality, soil productivity, and crop yields can be expected to follow. Mined soils can be restored through conservation management practices that increase soil organic material and eventually re-establish a balanced phosphorus cycle.

Model simulation results for phosphorus inputs

Phosphorus inputs from commercial fertilizers and manure, as represented in the EPIC model simulations, totaled 2.2 million tons per year (table 52). Most of the phosphorus was applied as commercial fertilizer. Manure phosphorus accounted for about 20 percent of the phosphorus applied; in comparison, only about 5 percent of the nitrogen sources came from manure. For the 298 million acres of cropland included in the study, the average phosphorus application rate was about 15 pounds per acre per year—about 12 pounds per acre as commercial fertilizer phosphorus (in inorganic form) and about 3 pounds per acre as manure phosphorus (in both inorganic and organic form), on average (table 53). (Sources of phosphorus as reported here are as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.)

Figure 26 Phosphorus cycle as modeled in EPIC

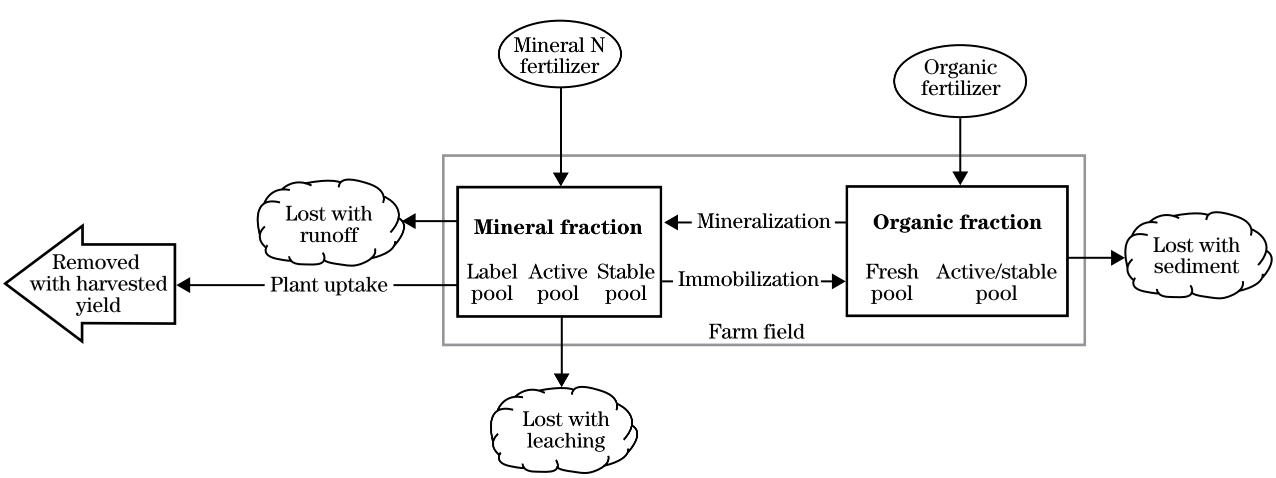


Table 52 Sources of phosphorus inputs–by region and by crop (average annual values)

	Acres		Commercial fertilizer		Manure		Sum of inputs	
	1,000s	**Percent**	**Tons**	**Percent**	**Tons**	**Percent**	**Tons**	**Percent**
By region								
Northeast	13,642	4.6	100,822	5.8	50,486	10.9	151,308	6.9
Northern Great Plains	72,397	24.3	299,275	17.3	71,124	15.3	370,399	16.9
South Central	45,350	15.2	231,967	13.4	41,300	8.9	273,266	12.4
Southeast	13,394	4.5	101,836	5.9	50,268	10.8	152,104	6.9
Southern Great Plains	32,096	10.8	136,179	7.9	39,427	8.5	175,606	8.0
Upper Midwest	112,581	37.7	797,236	46.1	178,282	38.3	975,518	44.4
West	9,018	3.0	63,430	3.7	34,094	7.3	97,525	4.4
All regions	298,478	100.0	1,730,744	100.0	464,982	100.0	2,195,726	100.0
By crop								
Barley	4,635	1.6	40,070	2.3	1,100	0.2	41,170	1.9
Corn	78,219	26.2	805,945	46.6	247,947	53.3	1,053,892	48.0
Corn silage	5,197	1.7	40,338	2.3	99,277	21.4	139,615	6.4
Cotton	16,858	5.6	98,627	5.7	6,793	1.5	105,420	4.8
Grass hay	14,596	4.9	31,354	1.8	42,290	9.1	73,644	3.4
Legume hay	24,776	8.3	86,013	5.0	8,681	1.9	94,695	4.3
Oats	3,772	1.3	18,847	1.1	431	0.1	19,278	0.9
Peanuts	1,843	0.6	13,284	0.8	823	0.2	14,107	0.6
Potatoes	987	0.3	28,946	1.7	711	0.2	29,658	1.4
Rice	3,637	1.2	17,773	1.0	4	0.0	17,777	0.8
Spring wheat	20,503	6.9	97,332	5.6	2,092	0.4	99,424	4.5
Sorghum	10,897	3.7	62,707	3.6	8,681	1.9	71,388	3.3
Soybeans	67,543	22.6	178,549	10.3	31,974	6.9	210,523	9.6
Winter wheat	45,014	15.1	210,958	12.2	14,178	3.0	225,136	10.3
All crops	298,478	100.0	1,730,744	100.0	464,982	100.0	2,195,726	100.0

Note: Sources of phosphorus as reported here are as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

Table 53 Sources of phosphorus inputs on a per-acre basis–by region and by crop within regions (average annual values)

	Crop	Acres (1,000s)	Commercial fertilizer (lb/a)	Manure (lb/a)	Sum of inputs (lb/a)
By region					
Northeast	All crops	13,642	14.8	7.4	22.2
Northern Great Plains	All crops	72,397	8.3	2.0	10.2
South Central	All crops	45,350	10.2	1.8	12.0
Southeast	All crops	13,394	15.2	7.5	22.7
Southern Great Plains	All crops	32,096	8.5	2.5	10.9
Upper Midwest	All crops	112,581	14.2	3.2	17.3
West	All crops	9,018	14.1	7.6	21.6
All regions	All crops	298,478	11.6	3.1	14.7
By crop within region*					
Northeast	Corn	2,943	23.4	11.2	34.6
	Corn silage	1,482	18.6	33.7	52.3
	Grass hay	2,369	4.5	2.2	6.6
	Legume hay	4,052	7.0	0.4	7.3
	Oats	362	22.9	0.4	23.3
	Soybeans	1,305	20.1	7.2	27.3
	Winter wheat	853	21.1	1.4	22.6
Northern Great Plains	Barley	3,243	14.9	0.1	15.0
	Corn	15,466	12.2	6.4	18.6
	Corn silage	810	10.2	27.6	37.9
	Grass hay	2,443	4.5	1.5	6.0
	Legume hay	6,152	6.9	0.5	7.5
	Oats	1,255	7.3	0.0	7.3
	Spring wheat	18,916	8.6	0.0	8.6
	Sorghum	1,595	11.2	2.4	13.6
	Soybeans	9,562	2.6	0.5	3.1
	Winter wheat	12,748	6.2	0.4	6.6
South Central	Corn	5,956	23.6	3.8	27.4
	Cotton	5,487	12.9	0.2	13.1
	Grass hay	3,347	3.9	11.6	15.5
	Legume hay	1,630	6.9	0.4	7.3
	Peanuts	880	13.6	1.0	14.6
	Rice	3,004	7.9	0.0	7.9
	Sorghum	2,729	11.8	1.0	12.9
	Soybeans	14,083	5.4	0.7	6.1
	Winter wheat	7,896	9.7	0.1	9.9

Table 53 Sources of phosphorus inputs on a per-acre basis–by region and by crop within regions (average annual values)—Continued

	Crop	Acres (1,000s)	Commercial fertilizer (lb/a)	Manure (lb/a)	Sum of inputs (lb/a)
Southeast	Corn	3,028	22.8	11.3	34.1
	Corn silage	412	22.3	26.1	48.3
	Cotton	2,422	16.7	1.2	17.9
	Grass hay	2,000	4.1	11.4	15.5
	Legume hay	1,183	6.9	0.6	7.5
	Peanuts	479	14.3	1.6	15.9
	Soybeans	2,419	13.7	10.0	23.7
	Winter wheat	1,216	14.4	3.1	17.5
Southern Great Plains	Corn	2,665	11.2	19.3	30.5
	Cotton	7,316	10.1	0.1	10.2
	Legume hay	677	6.9	1.3	8.2
	Oats	503	6.5	0.2	6.7
	Peanuts	484	16.0	0.1	16.1
	Sorghum	4,895	10.7	1.9	12.6
	Winter wheat	15,037	6.4	0.5	6.9
Upper Midwest	Corn	47,941	23.2	5.1	28.3
	Corn silage	1,947	14.0	42.2	56.2
	Grass hay	4,044	4.5	1.6	6.2
	Legume hay	9,233	7.0	0.4	7.3
	Oats	1,388	7.9	0.1	8.0
	Spring wheat	815	14.8	0.1	14.9
	Sorghum	1,604	12.2	0.5	12.7
	Soybeans	40,049	4.9	0.4	5.3
	Winter wheat	5,147	23.7	0.1	23.8
West	Barley	958	22.5	1.3	23.8
	Corn silage	297	13.4	85.6	99.0
	Cotton	1,631	7.3	5.5	12.8
	Legume hay	1,847	6.9	3.8	10.7
	Potatoes	329	76.0	1.7	77.8
	Rice	599	18.6	0.0	18.6
	Spring wheat	772	27.1	5.2	32.2
	Winter wheat	2,118	5.9	4.1	10.1

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.
Note: Sources of phosphorus as reported here are as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

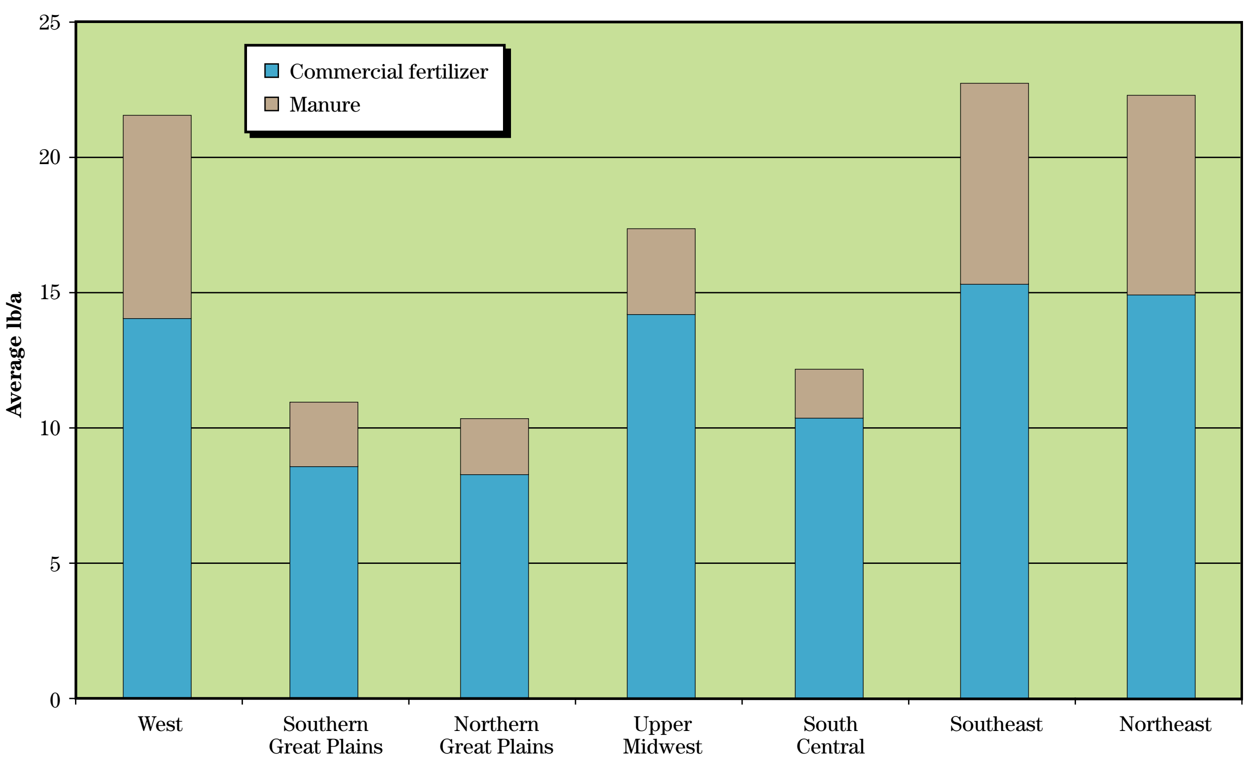
Spatial trends in phosphorus application rates

The spatial distribution of phosphorus applications represented in the EPIC model simulations are shown in map 26 for commercial fertilizer and map 27 for manure. The manure application rates shown in map 27 reflect the same spatial trends as in map 14 for manure nitrogen, where the yellow, orange, and red colors are indicative of intensive livestock production. There are marked differences, however, in the spatial trends for phosphorus and nitrogen applied as commercial fertilizer. As was the case for the commercial nitrogen fertilizer map, phosphorus application rates vary substantially within localized areas reflecting the crop mix and differences in application rates by crop. The yellows and greens in the maps are below the overall average phosphorus application rate. The reds and oranges represent areas with above-average application rates. In contrast to the spatial trends in nitrogen application rates, average phosphorus application rates were much lower throughout areas west of the Mississippi River than cropland in the East, reflecting much lower percentages of acres receiving commercial phosphorus fertilizers for crops grown in those parts of the country. The highest commercial phosphorus fertilizer application rates shown in map 26 are in the potato growing areas of the country, and the lowest occur throughout most of the Great Plains states.

Phosphorus input estimates by region

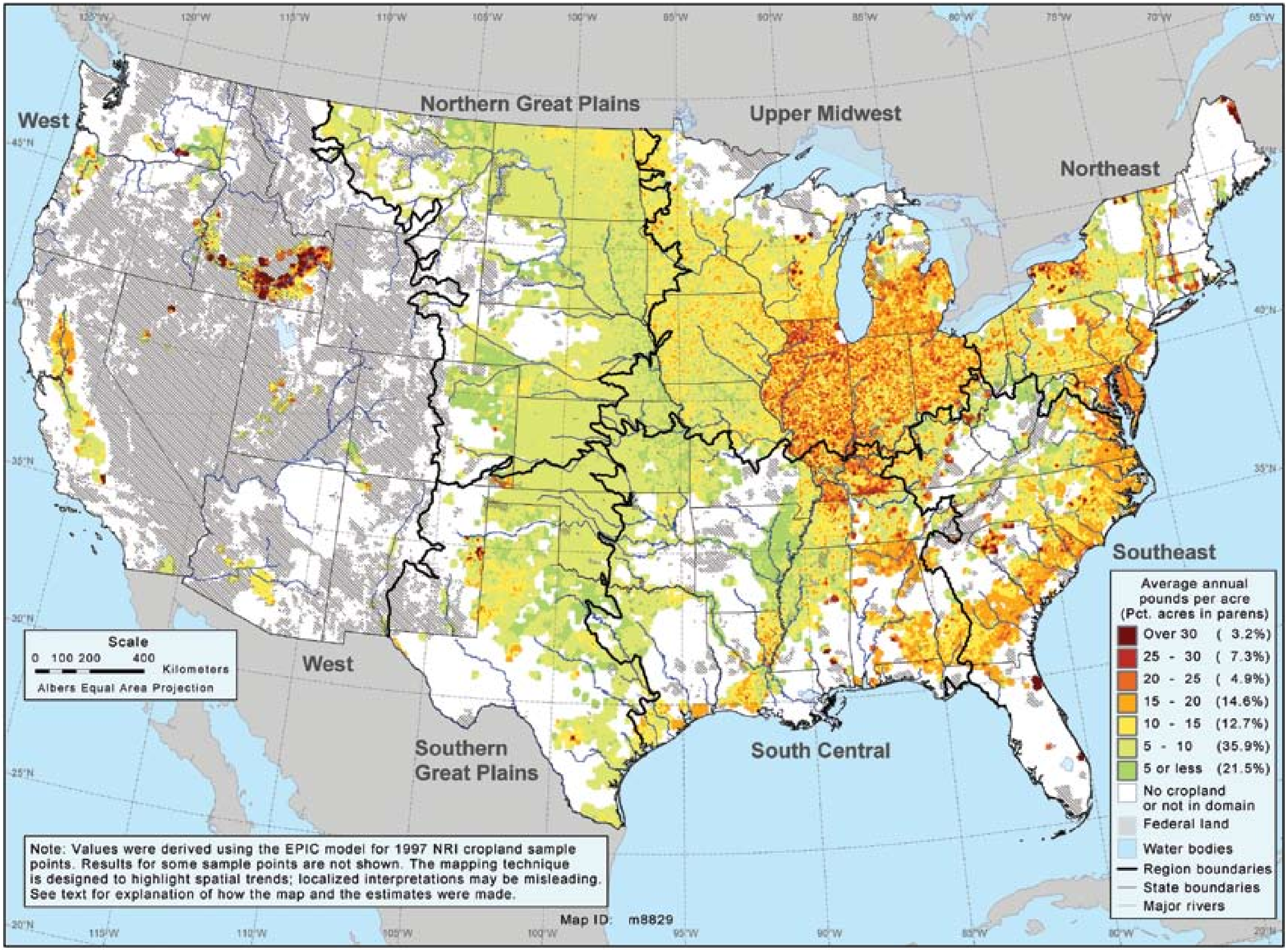
The highest per-acre phosphorus applications, on average, were in three regions—the Southeast region (23 lb/a), the Northeast region (22 lb/a), and the West region (22 lb/a) (fig. 27, table 53). About a third of the phosphorus applied in these regions was as manure applications. The South Central, Northern Great Plains, and Southern Great Plains regions had much lower phosphorus inputs, averaging about 10 to 12 pounds per acre, with only about a fifth coming from manure. The Upper Midwest region had an average phosphorus application of 17 pounds per acre, but accounted for 44 percent of all the phosphorus applied. As observed for nitrogen, phosphorus application in the Upper Midwest region was disproportionately high relative to acres of cropland (table 52).

Figure 27 Sources of per-acre phosphorus inputs–by region

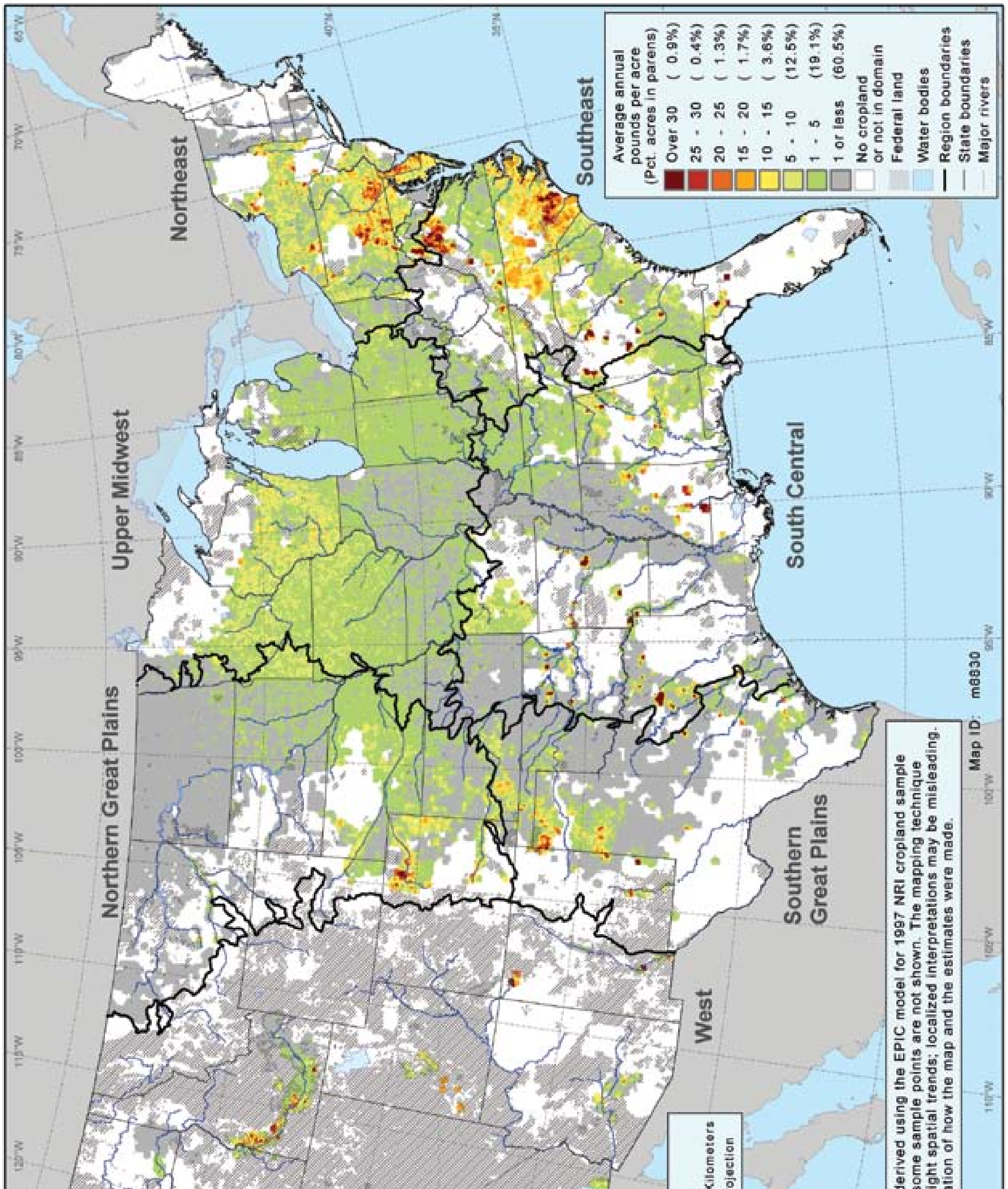


Note: Sources of phosphorus are reported here as elemental phosphorus.

Map 26 Average annual commercial fertilizer application rates for phosphorus (elemental P) in model simulations



Map 27 Average annual manure phosphorus application rates (elemental P) in model simulations



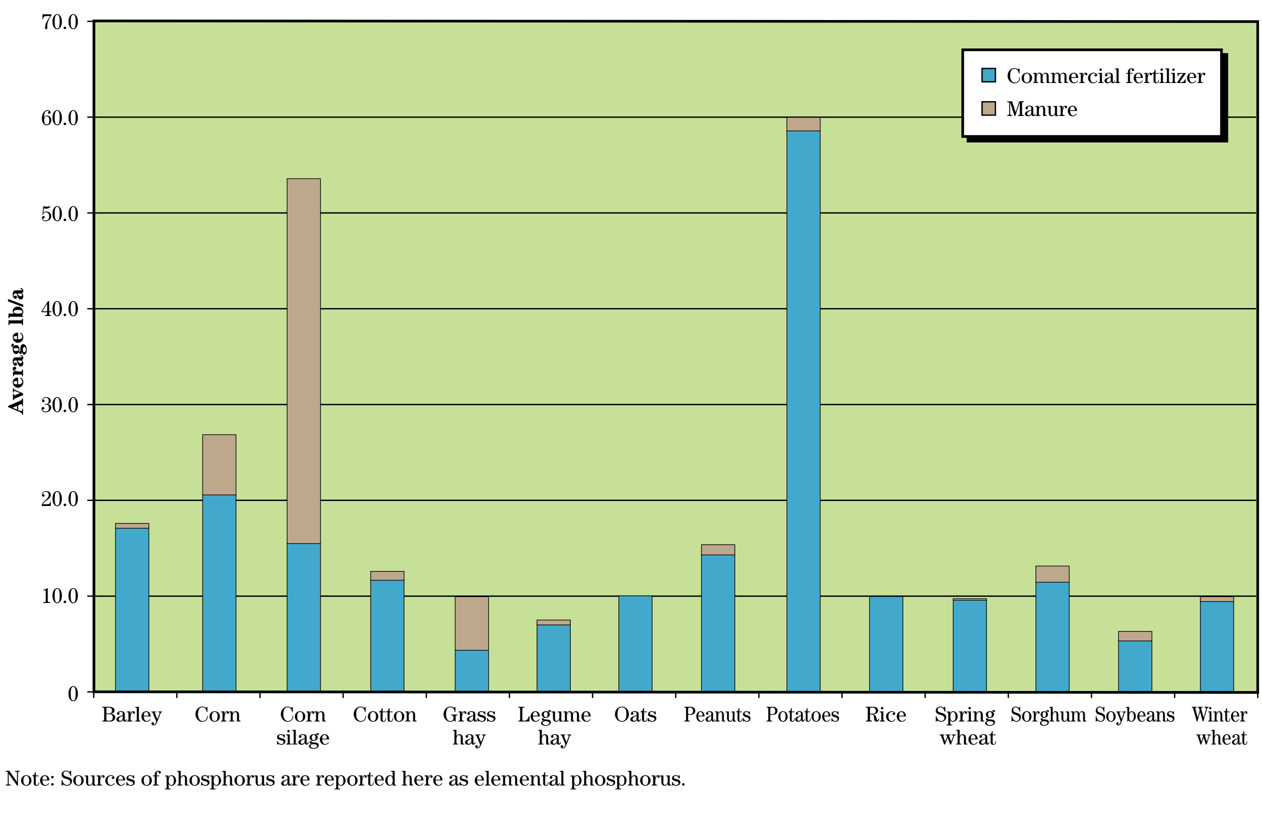
Phosphorus input estimates by crop

Over half of the phosphorus input was applied to corn and corn silage acres in these model simulations (table 52). The average phosphorus application rate (both commercial fertilizer and manure) was about 27 pounds per acre for corn and about 54 pounds per acre for corn silage. Most of the phosphorus applied to corn silage (71%) was applied as manure (fig. 28). Application rates for corn and corn silage were higher than all other crops in each region where these crops are commonly grown (table 53). Potatoes had the highest phosphorus application rate overall, averaging 60 pounds per acre and consisting almost entirely of phosphorus from commercial fertilizers (fig. 28). In the West region, phosphorus applications for potatoes averaged 78 pounds per acre, second only to corn silage in that region (table 53). For other crops, phosphorus application rates averaged less than 20 pounds per acre in most regions, and often less than 10 pounds per acre (table 53).

Model simulation results for phosphorus loss

Model simulation results indicated that a total of 360,000 tons of phosphorus was lost from cropland fields each year (table 54). This represents about 16 percent of the 2.2 million tons of phosphorus applied as commercial fertilizer and manure. In contrast, 28% of the nitrogen sources were lost from cropland fields each year. The average per-acre rate for phosphorus loss was 2.4 pounds per cropland acre. The predominate loss pathway (63% of total phosphorus loss) was phosphorus lost with waterborne sediment, with an average loss of 1.5 pounds per acre per year. Soluble phosphorus dissolved in surface water runoff, averaging about 0.5 pounds per acre per year, accounted for nearly 20 percent of the total phosphorus loss, whereas phosphorus dissolved in leachate accounted for less than 2 percent. Phosphorus loss with windborne sediment averaged 0.4 pounds per acre per year and accounted for 15 percent of the total phosphorus loss.

Figure 28 Sources of per-acre phosphorus inputs–by crop



Note: Sources of phosphorus are reported here as elemental phosphorus.

Table 54 Phosphorus loss estimates–by region and by crop (average annual values)

	Acres	Dissolved in surface water runoff		Dissolved in leachate		Lost with waterborne sediment		Lost with windborne sediment		Sum of all loss pathways	
	(Percent)	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
By region											
Northeast	4.6	4,811	6.9	684	9.5	23,387	10.3	282	0.5	29,163	8.1
Northern Great Plains	24.3	5,628	8.0	145	2.0	24,441	10.7	21,294	38.5	51,506	14.3
South Central	15.2	18,271	26.1	2,573	35.6	42,014	18.4	1,543	2.8	64,401	17.9
Southeast	4.5	5,850	8.4	984	13.6	10,814	4.7	19	0.0	17,667	4.9
Southern Great Plains	10.8	1,976	2.8	177	2.5	8,356	3.7	28,372	51.3	38,881	10.8
Upper Midwest	37.7	31,742	45.4	2,550	35.3	116,841	51.3	3,553	6.4	154,686	42.9
West	3.0	1,689	2.4	109	1.5	2,012	0.9	247	0.4	4,057	1.1
All regions	100.0	69,967	100.0	7,222	100.0	227,863	100.0	55,309	100.0	360,361	100.0
By crop											
Barley	1.6	682	1.0	20	0.3	1,671	0.7	777	1.4	3,151	0.9
Corn	26.2	30,909	44.2	2,057	28.5	118,168	51.9	20,200	36.5	171,334	47.5
Corn silage	1.7	2,299	3.3	158	2.2	18,067	7.9	1,552	2.8	22,075	6.1
Cotton	5.6	3,102	4.4	802	11.1	15,205	6.7	14,737	26.6	33,846	9.4
Grass hay	4.9	3,753	5.4	439	6.1	2,666	1.2	8	0.0	6,866	1.9
Legume hay	8.3	1,594	2.3	380	5.3	52	0.0	2	0.0	2,028	0.6
Oats	1.3	815	1.2	64	0.9	2,872	1.3	366	0.7	4,116	1.1
Peanuts	0.6	245	0.4	131	1.8	869	0.4	772	1.4	2,018	0.6
Potatoes	0.3	369	0.5	40	0.6	1,088	0.5	340	0.6	1,836	0.5
Rice	1.2	2,418	3.5	420	5.8	2,871	1.3	13	0.0	5,721	1.6
Spring wheat	6.9	1,924	2.7	10	0.1	6,047	2.7	3,574	6.5	11,555	3.2
Sorghum	3.7	1,552	2.2	132	1.8	6,646	2.9	7,582	13.7	15,912	4.4
Soybeans	22.6	14,558	20.8	1,975	27.3	37,553	16.5	2,993	5.4	57,079	15.8
Winter wheat	15.1	5,748	8.2	594	8.2	14,087	6.2	2,393	4.3	22,822	6.3
All crops	100.0	69,967	100.0	7,222	100.0	227,863	100.0	55,309	100.0	360,361	100.0

Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

The spatial distribution of the sum of all phosphorus loss pathways is shown in map 28. The areas most susceptible to phosphorus losses are colored dark red, representing 4 percent of the cropland acres included in the study, and red, representing 6 percent of the cropland. The largest area of cropland most susceptible to phosphorus loss is in Pennsylvania, western Maryland, and parts of New York; the average phosphorus loss exceeds 9 pounds per acre per year in many areas in south central Pennsylvania. Another large vulnerable area extends south from southern Indiana, southern Illinois, and eastern Kentucky to central Louisiana. Smaller vulnerable areas include: the rice growing region in Louisiana and southeast Texas; the Texas panhandle region where windborne sediment losses are high; an area in eastern Iowa; northwestern Illinois; and southwestern Wisconsin; a small area in eastern North Carolina where average losses exceed 9 pounds per acre per year; and the Willamette River Basin in Oregon. Other hot spots are more localized.

Per-acre phosphorus loss estimates for four loss pathways

The spatial distribution of phosphorus loss for three of the phosphorus loss pathways is shown in maps 29–31. Class breaks used to make the maps are the same for phosphorus lost with waterborne and windborne sediment, but differ in the map showing phosphorus dissolved in surface water runoff because of the much lower levels. The spatial distribution of phosphorus dissolved in leachate is not shown because of the low level of phosphorus loss for this loss pathway. (Phosphorus dissolved in lateral subsurface flow is theoretically possible, but was negligible in these model simulations and thus not addressed in the analysis.)

Phosphorus lost with waterborne sediment—Map 29 shows the spatial distribution of phosphorus lost with waterborne sediment. The red and brown colored areas in the map have average loss estimates of 5 pounds per acre per year or more and represent about 6 percent of the acres included in the study. The cropland areas most susceptible to phosphorus loss were similar to those for nitrogen (map 17), except in regions where phosphorus was applied less frequently than nitrogen (such as the wheat growing areas). The area of highest vulnerability for phosphorus loss with waterborne sediment—central and southern Pennsylvania and northern Maryland—is more pronounced for phosphorus loss than for nitrogen loss. Similarly, the Midwest and areas along the Ohio River and lower Mississippi River, which are vulnerable areas for both nitrogen and phosphorus loss with waterborne sediment, tend to have fewer localized areas with the highest phosphorus loss estimates than was the case for nitrogen. The least vulnerable acres—colored green or gray in the map and having average loss estimates of 1 pound per acre or less—represent over half of the cropland acres.

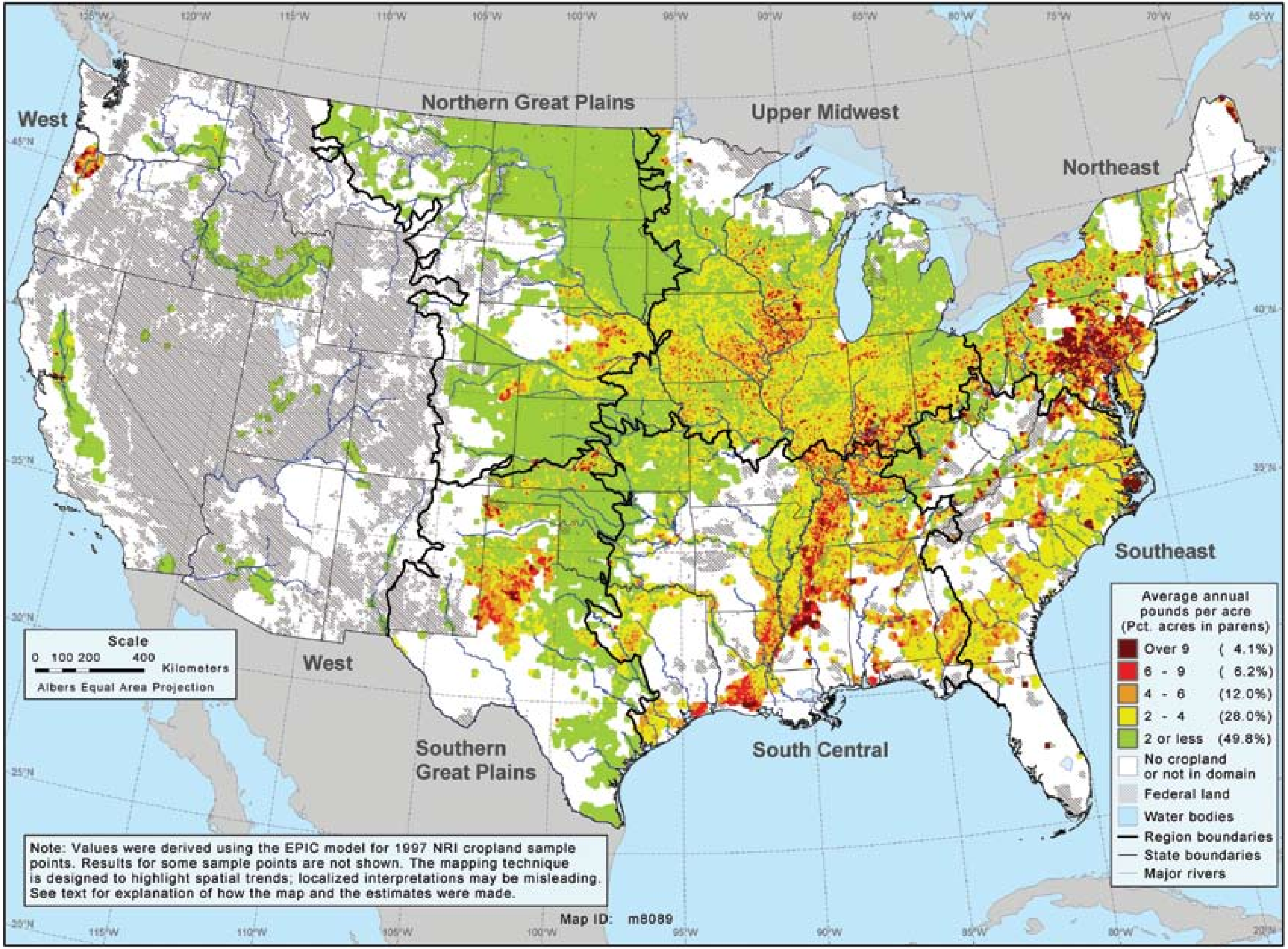
Phosphorus lost with windborne sediment—Areas of greatest vulnerability for phosphorus lost with windborne sediment are in the most vulnerable wind erosion areas, as shown in map 30**.**

Phosphorus dissolved in surface water runoff—The spatial distribution of phosphorus loss dissolved in surface water runoff is shown in map 31**.** The red areas in the map have average estimates of phosphorus dissolved in surface water runoff of more than 2 pounds per acre per year. These areas represent about 2 percent of the acres included in the study. The least vulnerable areas—colored green in the map—have average loss estimates of 0.5 pounds per acre per year or less, and represent two-thirds of the cropland acres.

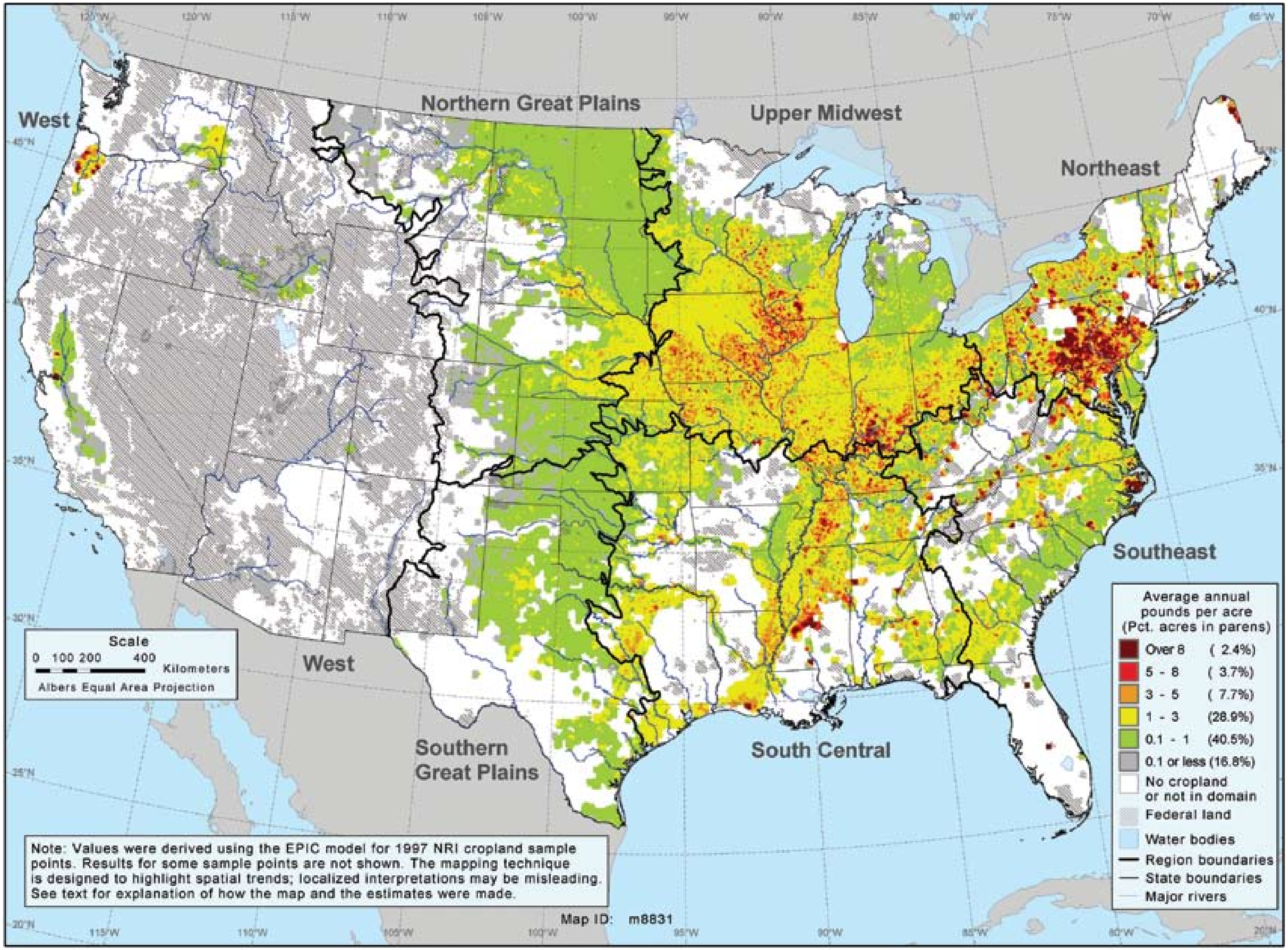
While generally similar to the spatial distribution of nitrogen dissolved in surface water runoff (map 19), the spatial distribution of phosphorus dissolved in surface water runoff differs in some important ways. Most notably, the areas in the West that had the highest potential for loss of nitrogen dissolved in surface water runoff had, for the most part, low vulnerability for dissolved phosphorus runoff loss. Similarly, the rice-growing area along the Mississippi River in Arkansas was highly vulnerable to nitrogen runoff, but only modestly so for phosphorus. The rice growing region in Texas and southern Louisiana, however, had both high nitrogen and phosphorus loss dissolved in runoff. Hot spots in Virginia and North Carolina were much more pronounced for phosphorus than for nitrogen. In addition, an area of high levels of phosphorus dissolved in surface water runoff, but modest amounts of nitrogen loss dissolved in surface water runoff was in southern Illinois, eastern Kentucky and eastern Tennessee, and parts of northern Alabama.

Phosphorus dissolved in leachate—Phosphorus loss dissolved in leachate averaged less than 0.1 pounds per acre per year, with average estimates for some crops in some regions only as high as 0.3 pounds

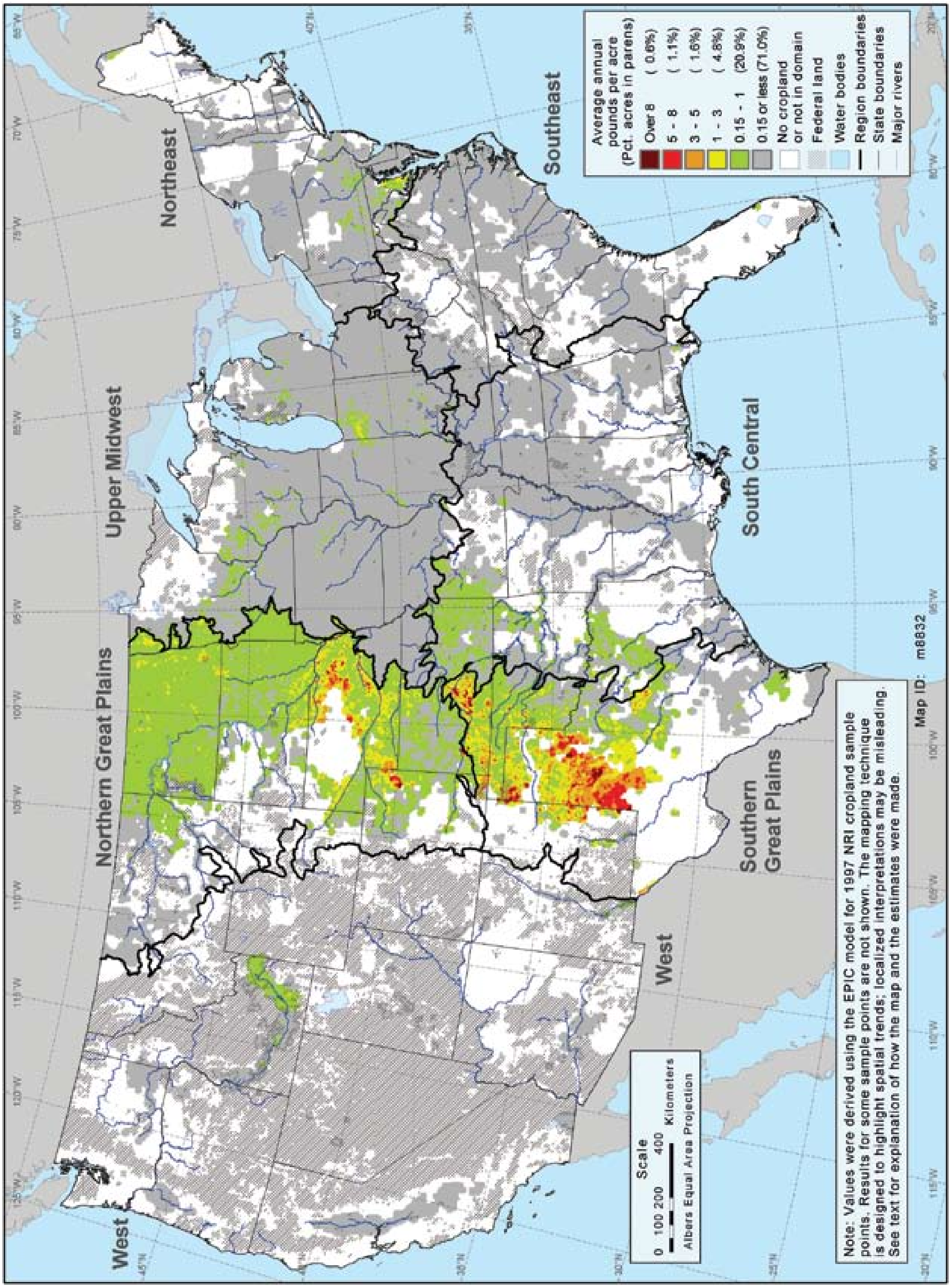
Map 28 Estimated average annual per-acre phosphorus loss summed over all loss pathways (elemental P)



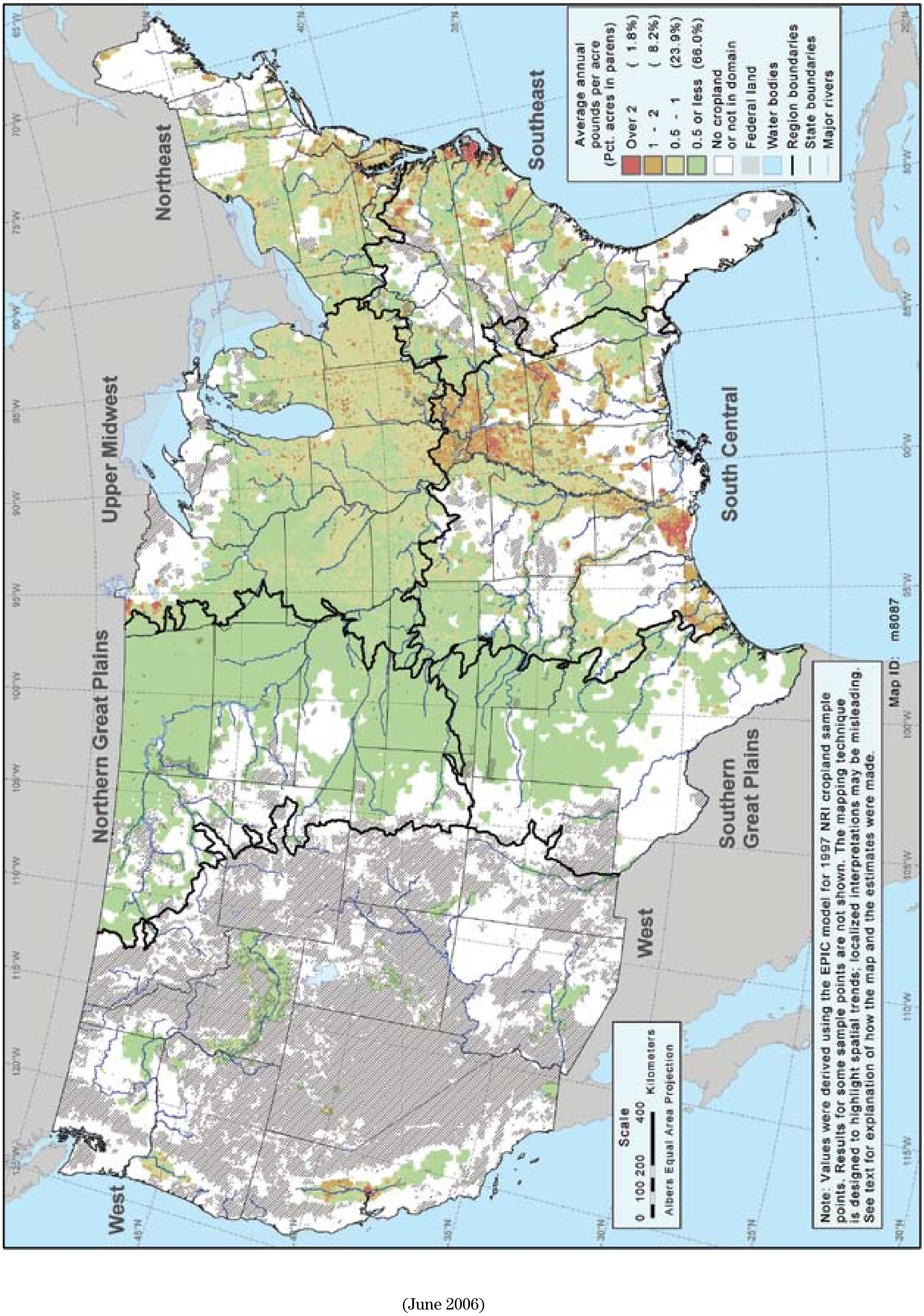
Map 29 Estimated average annual per-acre phosphorus lost with waterborne sediment (elemental P)



Map 30 Estimated average annual per-acre phosphorus lost with windborne sediment (elemental P)



Map 31 Estimated average annual per-acre phosphorus dissolved in surface water runoff (elemental P)



per acre per year (table 55). The amount dissolved in leachate was minimal except in coarse textured and organic soils.

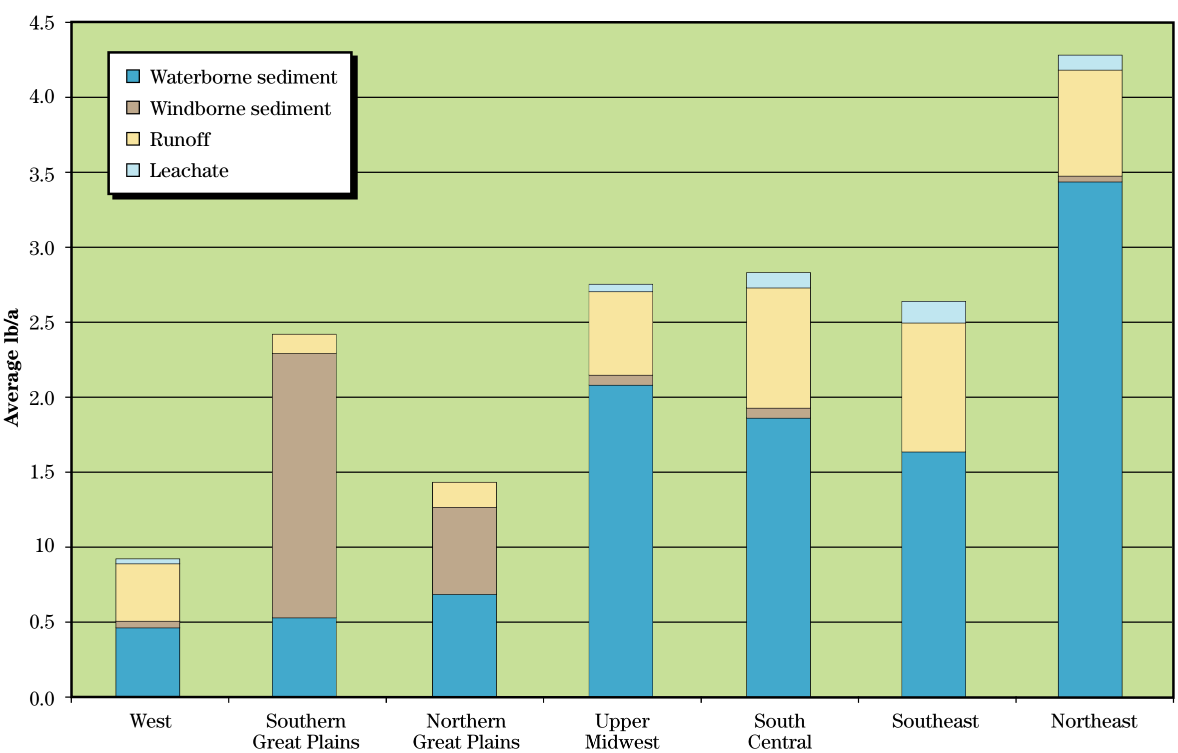
Per-acre phosphorus loss by region

Northeast region—Phosphorus losses were highest in the Northeast region, averaging 4.3 pounds per cropland acre per year (fig. 29, table 55), about twice the national average. Most (80%) was lost with waterborne sediment, but an average of 0.7 pounds per acre per year was lost as dissolved phosphorus in surface water runoff, representing about 15 percent of the total loss in the Northeast region. Overall, phosphorus loss in the Northeast region represented about 19 percent of the annual phosphorus inputs.

Corn silage in the Northeast had the highest phosphorus loss of any crop in any region, averaging nearly 14 pounds per acre per year for phosphorus loss summed over all pathways. Phosphorus loss for corn acres was also among the highest in any region, averaging nearly 8 pounds per acre per year.

South Central, Upper Midwest, and Southeast regions—The South Central, Upper Midwest, and Southeast regions each averaged about 2.6 to 2.8 pounds of phosphorus loss per acre of cropland (table 55, fig. 29). The majority of phosphorus loss in these regions was with waterborne sediment (61–76%). Per-acre losses of phosphorus dissolved in runoff and leachate were greater in the Southeast and South Central regions than in other regions, averaging 0.9 and 0.8 pounds per acre for runoff, respectively, and 0.15 and 0.11 pounds per acre for leachate, respectively. Phosphorus dissolved in surface water runoff accounted for 33 and 28 percent of phosphorus losses in the Southeast and South Central regions, respectively. Estimates of phosphorus loss in surface water runoff was lower in the Upper Midwest region, but still significant. High losses of phosphorus dissolved in runoff and leachate are indicative of high phosphorus levels in cropland soils, as the propensity for phosphorus to dissolve in water increases dramatically as soil phosphorus levels increase.

Figure 29 Average annual per-acre estimates of phosphorus loss–by region



Note: Phosphorus loss is reported here as elemental phosphorus.

Table 55 Phosphorus loss estimates on a per-acre basis–by region and by crop within regions (average annual values)

	Crop	Acres (1,000s)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Sum of all loss pathways (lb/a)
By region							
Northeast	All crops	13,642	0.7	0.1	3.4	<0.1	4.3
Northern Great Plains	All crops	72,397	0.2	<0.1	0.7	0.6	1.4
South Central	All crops	45,350	0.8	0.1	1.9	0.1	2.8
Southeast	All crops	13,394	0.9	0.2	1.6	<0.1	2.6
Southern Great Plains	All crops	32,096	0.1	<0.1	0.5	1.8	2.4
Upper Midwest	All crops	112,581	0.6	0.1	2.1	0.1	2.8
West	All crops	9,018	0.4	<0.1	0.5	0.1	0.9
All regions	All crops	298,478	0.5	<0.1	1.5	0.4	2.4
By crop within region*							
Northeast	Corn	2,943	1.2	0.1	6.2	0.1	7.7
	Corn silage	1,482	1.1	0.1	12.5	0.1	13.8
	Grass hay	2,369	0.6	0.1	0.6	<0.1	1.3
	Legume hay	4,052	0.2	0.1	<0.1	<0.1	0.3
	Oats	362	1.1	0.1	4.0	<0.1	5.2
	Soybeans	1,305	0.8	0.2	2.6	0.1	3.6
	Winter wheat	853	0.7	0.1	2.3	<0.1	3.2
Northern Great Plains	Barley	3,243	0.2	<0.1	0.5	0.4	1.1
	Corn	15,466	0.3	<0.1	1.4	1.5	3.2
	Corn silage	810	0.3	<0.1	2.2	2.3	4.8
	Grass hay	2,443	0.1	<0.1	0.1	<0.1	0.2
	Legume hay	6,152	0.1	<0.1	<0.1	<0.1	0.1
	Oats	1,255	0.1	<0.1	0.7	0.4	1.3
	Spring wheat	18,916	0.1	<0.1	0.6	0.4	1.1
	Sorghum	1,595	0.1	<0.1	1.1	1.5	2.7
	Soybeans	9,562	0.2	<0.1	0.7	0.5	1.3
	Winter wheat	12,748	0.1	<0.1	0.2	0.1	0.4
South Central	Corn	5,956	1.7	0.1	3.8	0.1	5.8
	Cotton	5,487	0.7	0.2	3.7	<0.1	4.5
	Grass hay	3,347	0.8	0.1	0.5	<0.1	1.4
	Legume hay	1,630	0.2	0.1	<0.1	<0.1	0.2
	Peanuts	880	0.3	0.2	1.0	0.2	1.7
	Rice	3,004	1.3	0.3	1.8	<0.1	3.4
	Sorghum	2,729	0.5	0.1	2.0	0.5	3.1
	Soybeans	14,083	0.7	0.1	1.2	<0.1	2.0
	Winter wheat	7,896	0.5	0.1	1.2	<0.1	1.8

Table 55 Phosphorus loss estimates on a per-acre basis–by region and by crop within regions (average annual values)—Continued

	Crop	Acres (1,000s)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Sum of all loss pathways (lb/a)
Southeast	Corn	3,028	1.9	0.1	2.5	<0.1	4.6
	Corn silage	412	1.4	0.1	6.9	<0.1	8.3
	Cotton	2,422	0.5	0.2	1.9	<0.1	2.5
	Grass hay	2,000	0.5	0.1	0.5	<0.1	1.2
	Legume hay	1,183	0.2	0.1	<0.1	<0.1	0.2
	Peanuts	479	0.3	0.2	1.0	<0.1	1.5
	Soybeans	2,419	0.7	0.2	0.9	<0.1	1.8
	Winter wheat	1,216	0.8	0.2	1.8	<0.1	2.8
Southern Great Plains	Corn	2,665	0.3	<0.1	1.1	4.1	5.5
	Cotton	7,316	0.1	<0.1	0.8	4.0	4.9
	Legume hay	677	0.1	<0.1	<0.1	<0.1	0.1
	Oats	503	0.3	<0.1	0.6	0.1	1.1
	Peanuts	484	0.1	<0.1	0.8	2.9	3.8
	Sorghum	4,895	0.1	<0.1	0.6	2.3	3.1
	Winter wheat	15,037	0.1	<0.1	0.3	0.2	0.6
Upper Midwest	Corn	47,941	0.8	0.1	3.4	0.1	4.3
	Corn silage	1,947	0.8	<0.1	5.9	0.2	7.0
	Grass hay	4,044	0.5	<0.1	0.3	<0.1	0.8
	Legume hay	9,233	0.1	<0.1	<0.1	<0.1	0.2
	Oats	1,388	0.5	<0.1	1.8	0.1	2.4
	Spring wheat	815	0.9	<0.1	0.8	0.1	1.8
	Sorghum	1,604	0.4	<0.1	1.9	0.1	2.4
	Soybeans	40,049	0.4	<0.1	1.1	<0.1	1.6
	Winter wheat	5,147	0.7	<0.1	1.1	<0.1	1.9
West	Barley	958	0.3	<0.1	0.9	0.1	1.4
	Corn silage	297	1.1	0.1	0.7	0.1	2.0
	Cotton	1,631	0.2	<0.1	0.1	<0.1	0.4
	Legume hay	1,847	0.2	<0.1	<0.1	<0.1	0.2
	Potatoes	329	0.5	<0.1	0.2	0.5	1.2
	Rice	599	1.2	0.1	0.4	<0.1	1.6
	Spring wheat	772	0.4	<0.1	0.6	0.1	1.1
	Winter wheat	2,118	0.2	<0.1	0.8	<0.1	1.1

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

The highest per-acre phosphorus loss estimates were for corn and corn silage in the Southeast and Upper Midwest regions, and corn and cotton acres in the South Central region (table 55).

The South Central region had the largest percentage of annual phosphorus inputs lost from farm fields of all the regions—24 percent. Phosphorus loss as a percent of inputs was 12 percent in the Southeast region and 16 percent in the Upper Midwest region.

Southern Great Plains region—The average per-acre phosphorus loss in the Southern Great Plains region was 2.4 pounds per acre, equal to the national average (table 55). However, the principal loss pathway in the Southern Great Plains region was with windborne sediment. Phosphorus lost with windborne sediment accounted for 73 percent of the phosphorus loss in this region. Waterborne sediment accounted for most of the remaining phosphorus loss. The highest per-acre phosphorus loss estimates in the region were for corn and cotton. Overall phosphorus loss in the Southern Great Plains region represented 22 percent of the phosphorus inputs, the second highest percentage among the seven regions.

Northern Great Plains region—The Northern Great Plains region had low phosphorus losses from cropland fields, averaging only 1.4 pounds per cropland acre per year (fig. 29, table 55). This region also had the lowest per-acre loss of nitrogen. Farmer surveys show that wheat, which is the dominant crop in this region, often receives the lowest phosphorus application rates of any of the major field crops, and more than half of the wheat acres receive no phosphorus application. About equal amounts of phosphorus are lost with windborne and waterborne sediment, and only about 11 percent is lost as dissolved phosphorus in surface water runoff. Total phosphorus loss as a percent of inputs was 14 percent.

West region—The lowest per-acre phosphorus loss was in the West region, where phosphorus loss from all pathways averaged about 1 pound per acre, despite relatively high phosphorus inputs. Only 4 percent of the phosphorus applied was lost from cropland fields in the West region, compared to the national average of 16 percent. About half was lost with waterborne sediment and most of the rest as dissolved phosphorus in surface water runoff.

Per-acre phosphorus loss by crop

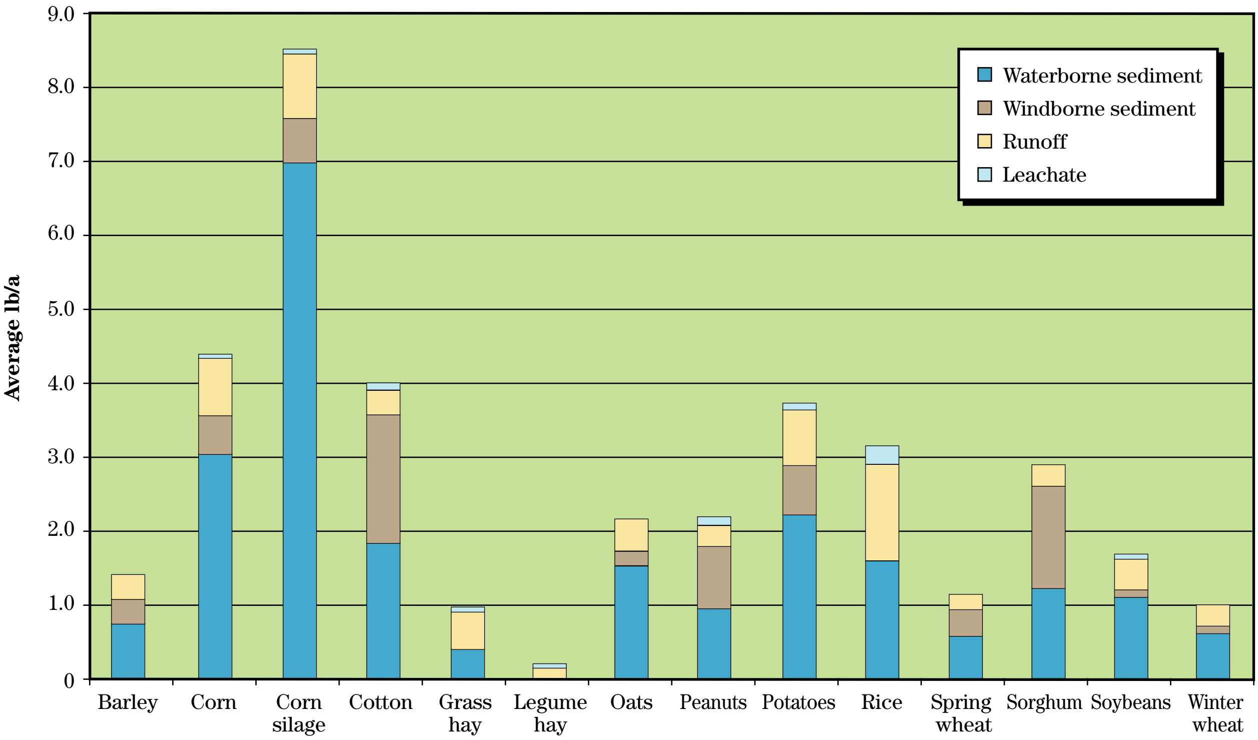
As shown previously for nitrogen loss, per-acre phosphorus loss estimates varied significantly by crop; however, crops with the highest phosphorus losses were not the same as those with the highest nitrogen losses. The crop with the highest per-acre phosphorus loss was corn silage (fig. 30), which had the second-highest phosphorus application rate, dominated by manure phosphorus. The average phosphorus loss for corn silage was 8.5 pounds per acre. Corn had the next highest average per-acre phosphorus loss at 4.4 pounds per acre, followed closely by cotton and potatoes. Potatoes, which had the highest average phosphorus application rate, had an average phosphorus loss of 3.7 pounds per acre, representing 6 percent of the phosphorus inputs. Legume hay had the lowest phosphorus loss, averaging only 0.2 pounds per acre. Phosphorus losses for barley, grass hay, spring wheat, and winter wheat were also low, averaging at or about 1 pound per acre per year.

For most comparisons between irrigated crops and non-irrigated crops, per-acre phosphorus loss estimates were about the same (table 56). Phosphorus loss for most crops in the West region was markedly lower than for non-irrigated crops, however. In contrast, phosphorus loss estimates for most crops in the Southern Great Plains region and for corn in the Northern Great Plains region was markedly higher for irrigated acres, primarily because phosphorus lost with windborne sediment was higher on these irrigated acres. In the Upper Midwest and South Central regions, corn had markedly lower phosphorus loss estimates for irrigated acres than for non-irrigated acres, primarily because phosphorus lost with waterborne sediment was lower on irrigated acres. Cotton acres in the South Central region and sorghum acres in the Southern Great Plains region also had markedly lower phosphorus loss estimates for irrigated acres than non-irrigated acres.

Tons of phosphorus loss

Total phosphorus loadings are obtained when the acres of cropland are taken into account. Estimates of the annual tons of phosphorus for each of the three principal loss pathways are shown in maps 32 through 34. Each dot on these three maps represents 100 tons of phosphorus loss from cropland acres to facilitate comparisons among the pathways. (Note that the nitrogen loading maps presently earlier were based on each dot representing 500 tons.)

Figure 30 Average annual per-acre estimates of phosphorus loss–by crop



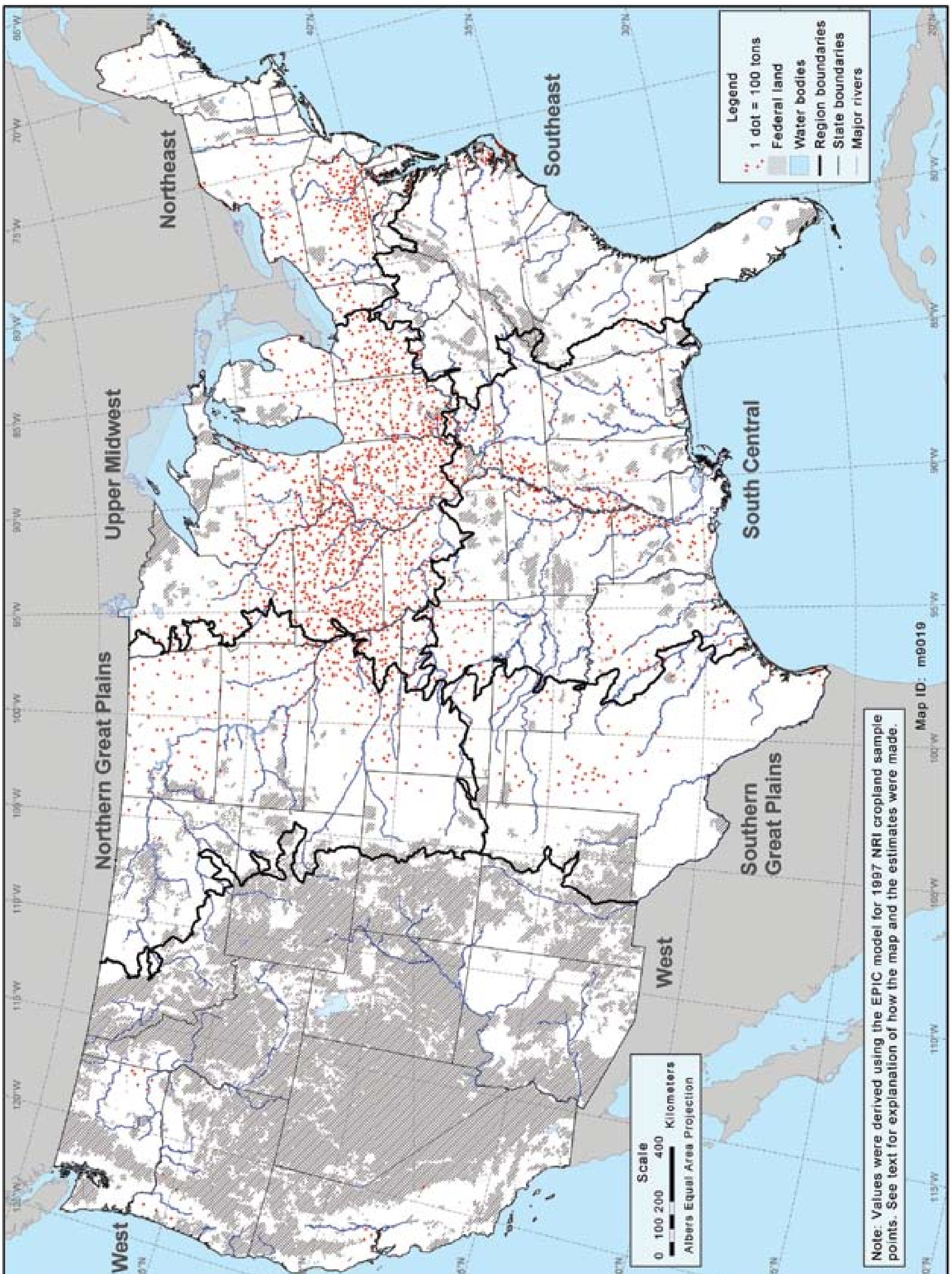
Note: Phosphorus loss is reported here as elemental phosphorus.

Table 56 Comparison of phosphorus loss estimates for irrigated crops to estimates for non-irrigated crops (average annual values)

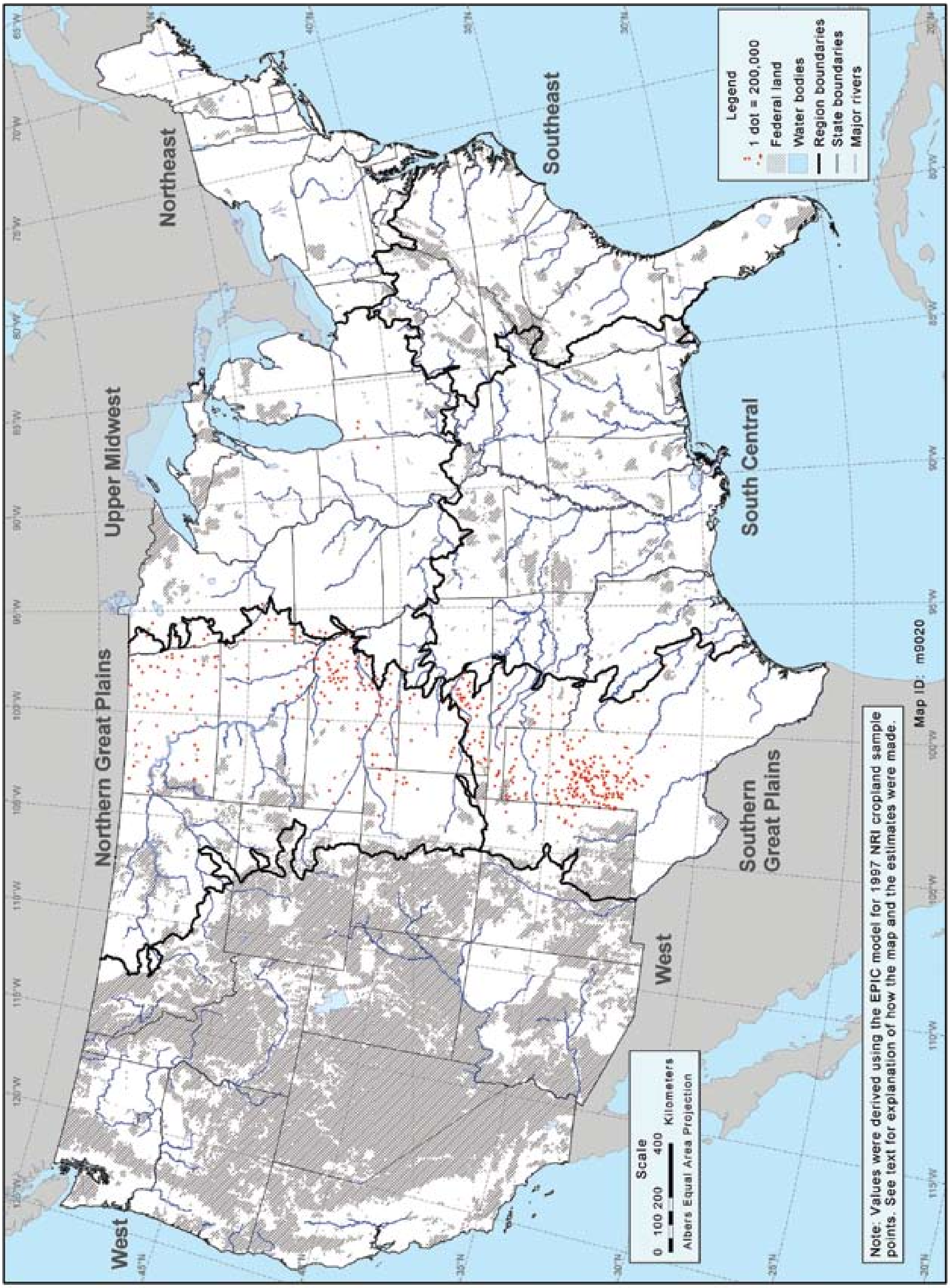
Region	Crop*	Acres (1,000s)		Sum of all loss pathways (lb/a)		Dissolved in surface water runoff (lb/a)		Dissolved in leachate (lb/a)		Lost with waterborne sediment (lb/a)		Lost with windborne sediment (lb/a)	
		Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Northern Great Plains	Corn	6,680	8,785	3.7	3.0	0.4	0.2	0.2	<0.1	1.4	1.4	1.8	1.3
	Legume hay	1,336	4,816	0.2	0.1	0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Soybeans	984	8,578	1.6	1.3	0.1	0.2	0.2	<0.1	0.8	0.7	0.5	0.5
	Winter wheat	662	12,086	0.6	0.4	0.2	0.1	0.1	<0.1	0.1	0.2	0.1	0.1
South Central	Corn	671	5,285	5.0	7.0	1.2	1.8	1.6	1.1	2.0	4.0	0.2	0.1
	Cotton	1,505	3,983	5.2	6.5	0.6	0.7	2.2	1.7	2.4	4.1	<0.1	<0.1
	Rice	3,004	0	5.7	NA	1.3	NA	2.5	NA	1.8	NA	<0.1	NA
	Soybeans	3,585	10,498	2.6	3.0	0.6	0.7	1.0	1.0	1.0	1.3	<0.1	0.1
	Winter wheat	554	7,341	3.0	2.3	0.6	0.5	1.4	0.6	0.9	1.2	<0.1	<0.1
Southeast	Cotton	307	2,115	3.5	4.3	0.3	0.5	1.9	1.9	1.3	1.9	<0.1	<0.1
Southern Great Plains	Corn	1,993	672	6.5	2.6	0.2	0.4	0.1	0.1	0.9	1.6	5.2	0.6
	Cotton	2,831	4,486	5.6	4.8	0.3	0.1	0.2	0.1	0.9	0.7	4.3	3.8
	Legume hay	414	263	0.2	0.1	0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	Peanuts	325	159	4.3	3.8	0.1	0.2	0.3	0.3	0.7	0.9	3.2	2.4
	Sorghum	1,147	3,748	2.2	3.5	0.2	0.1	0.1	0.1	0.4	0.7	1.5	2.6
	Winter wheat	1,991	13,046	0.5	0.7	0.1	0.1	0.1	0.1	0.1	0.3	0.1	0.2
Upper Midwest	Corn	1,517	46,424	3.6	4.8	0.6	0.8	1.1	0.5	1.8	3.5	0.1	0.1
	Soybeans	641	39,409	2.3	2.0	0.3	0.4	1.1	0.5	0.8	1.2	<0.1	<0.1
West	Barley	601	357	0.7	2.7	0.4	0.2	0.1	<0.1	0.1	2.3	0.1	0.1
	Corn silage	297	0	2.5	NA	1.1	NA	0.6	NA	0.7	NA	0.1	NA
	Cotton	1,631	0	0.5	NA	0.2	NA	0.1	NA	0.1	NA	<0.1	NA
	Legume hay	1,688	159	0.3	0.4	0.2	0.2	0.1	<0.1	<0.1	0.1	<0.1	<0.1
	Potatoes	329	0	1.2	NA	0.5	NA	<0.1	NA	0.2	NA	0.5	NA
	Rice	599	0	2.4	NA	1.2	NA	0.9	NA	0.4	NA	<0.1	NA
	Spring wheat	575	197	0.7	2.4	0.4	0.3	0.1	0.1	0.1	1.9	0.1	0.2
	Winter wheat	1,052	1,066	1.3	1.6	0.3	0.1	0.6	0.2	0.3	1.3	<0.1	<0.1

NA=not applicable.
* Irrigated crops with more than 250,000 acres in a region are included in the table. These 26 crop-region combinations represent 92 percent of the irrigated acres included in the study.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29

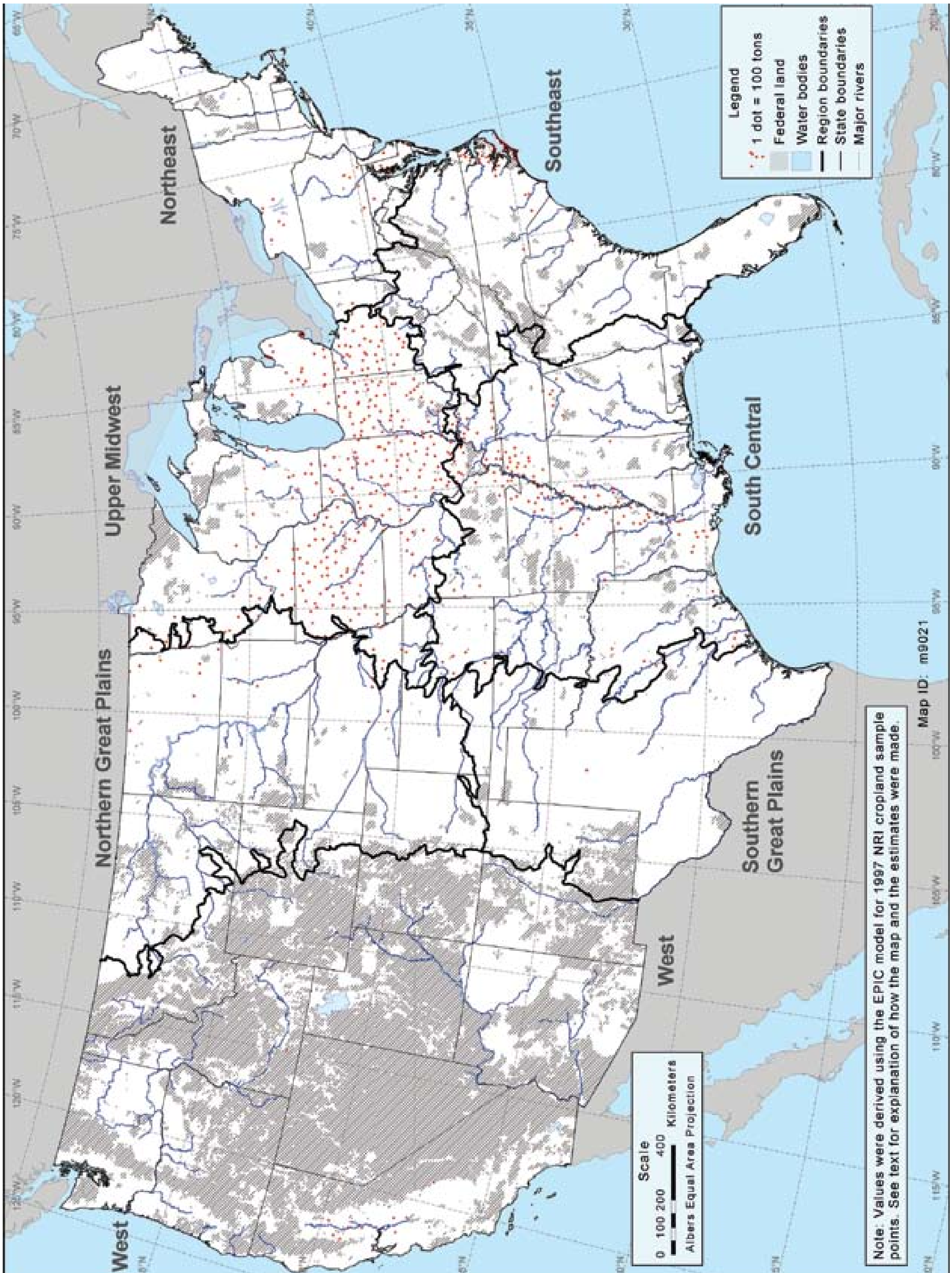
Map 32 Estimated average annual tons of phosphorus lost with waterborne sediment (elemental P)



Map 33 Estimated average annual tons of phosphorus lost with windborne sediment (elemental P)



Map 34 Estimated average annual tons of phosphorus dissolved in surface water runoff (elemental P)



In terms of loadings, the Upper Midwest region accounted for 43 percent of the total tons of phosphorus loss, over twice as much as any of the other six regions and disproportionately high relative to the percentage of acres represented by the region (table 57). About 37 percent of acres included in the study are in the Upper Midwest region. This disproportionality is largely explained, however, by the high proportion of phosphorus inputs for this region—44 percent.

Phosphorus losses were also disproportionately high relative to cropland acres in the Northeast region (table 57). Cropland acres in the Northeast represented only 4.6 percent of all cropland acres included in the study, but phosphorus losses represented 8 percent of total losses. This is also explained by the disproportionately high phosphorus inputs—7 percent of total phosphorus inputs occurred in the Northeast region.

The West region had the lowest phosphorus loadings, representing only 1 percent of total phosphorus losses. Phosphorus loss in the West region, as well as the Northern Great Plains region, was disproportionately low relative to cropland acres (table 57).

Among the 14 crops, corn accounted for the largest share of total phosphorus loss—48 percent, which is nearly twice the percentage of corn acres but equal to the share of phosphorus inputs for corn (table 57). Phosphorus loss was also disproportionately high for cotton and corn silage. Soybeans accounted for the second highest phosphorus loadings—16 percent, which was disproportionately low relative to acres (table 57). Crops associated with the lowest phosphorus loadings were oats, peanuts, potatoes, rice, and barley, largely because of the small number of acres for these crops. Legume hay was also among the crops with the lowest phosphorus loadings, accounting for only 0.6 percent of the total loadings while representing about 8 percent of the cropland acres.

Effects of soil properties on phosphorus loss
The relationships between phosphorus loss and soil texture and hydrologic soil group were nearly identical to relationships observed for nitrogen for each loss pathway (tables 58 and 59). Organic soils had extremely high losses, averaging 13.2 pounds per acre per year. Coarse and moderately course soils had the lowest losses for waterborne sediment and the highest losses for windborne sediment (table 58). For phosphorus loss dissolved in surface water runoff, hydrologic soil groups C and D had the highest losses and hydrologic soil groups A and B had the lowest losses (after adjusting for organic soils). For phosphorus dissolved in leachate, hydrologic soil group A soils and coarse textured and organic soils had the highest losses (except for the very small group of "other texture" soils).

Example of spatial variability of phosphorus loss
As shown previously for sediment and nitrogen losses, phosphorus losses also vary considerably at the local level. Figure 31 presents similar results for phosphorus loss for the two Iowa watersheds. Overall, commercial fertilizer and manure phosphorus inputs were about the same in both watersheds—about 16 pounds per acre, of which about a fourth was from manure applications. Total phosphorus loss was higher in the Lower Iowa watershed (4.4 lb/a/yr) than in the Floyd watershed (2.7 lb/a/yr).

Variability in phosphorus loss summed over all pathways by soil cluster was quite high in the Lower Iowa watershed, ranging from 0.5 to 14.3 pounds per acre. Variability was less in the Floyd watershed, where total phosphorus loss ranged from 0.6 to 4.0 pounds per acre. In the Lower Iowa watershed, the highest losses occurred on soils with few acres—the nine soil clusters with the highest losses (6 lb/a or more) accounted for 29 percent of the total phosphorus loss, but represented only 14 percent of the cropland acres. In the Floyd watershed, about 43 percent of the total phosphorus loss was associated with the three soil clusters with the highest loss rates (greater than 3 lb/a), representing 30 percent of the acres. Many of the soils with high phosphorus loss were different from the soils with high nitrogen loss in both watersheds, primarily because over 80 percent of the phosphorus loss was with waterborne sediment, whereas significant portions of nitrogen loss was through volatilization and leaching in these two watersheds.

Effects of tillage practices on phosphorus loss
Tillage practices were shown to have a significant influence on sediment loss and wind erosion estimates (tables 24 and 30) and a less pronounced influence on nitrogen loss estimates (table 41). The effect of tillage practices was larger for phosphorus loss than for nitrogen loss because the predominant loss pathway for phosphorus was waterborne and windborne sediment. As discussed earlier in this report (see table 12 and related discussion), the subset of model runs where all three tillage systems—conventional tillage, mulch till-

Table 57 Percentages by region and crop of the total for cropland acres, total phosphorus loss, and total phosphorus inputs

	Percent of total cropland acres	Percent of total phosphorus losses	Percent of all phosphorus sources
By region			
Disproportionately high phosphorus loss relative to acres			
Northeast	4.6	8.1	6.9
Upper Midwest	37.7	42.9	44.4
Disproportionately low phosphorus loss relative to acres			
Northern Great Plains	24.3	14.3	16.9
West	3.0	1.1	4.4
Phosphorus loss approximately proportional to acres			
South Central	15.2	17.9	12.4
Southeast	4.5	4.9	6.9
Southern Great Plains	10.8	10.8	8.0
All regions	100.0	100.0	100.0
By crop			
Disproportionately high phosphorus loss relative to acres			
Corn	26.2	47.5	48.0
Corn silage	1.7	6.1	6.4
Cotton	5.6	9.4	4.8
Disproportionately low phosphorus loss relative to acres			
Soybeans	22.6	15.8	9.6
Grass hay	4.9	1.9	3.4
Legume hay	8.3	0.6	4.3
Winter wheat	15.1	6.3	10.3
Spring wheat	6.9	3.2	4.5
Phosphorus loss approximately proportional to acres			
Barley	1.6	0.9	1.9
Oats	1.3	1.1	0.9
Peanuts	0.6	0.6	0.6
Potatoes	0.3	0.5	1.4
Rice	1.2	1.6	0.8
Sorghum	3.7	4.4	3.3
All crops	100.0	100.0	100.0

Table 58 Sources of phosphorus applied and estimates of phosphorus loss (elemental P)–by soil texture class (average annual values)

Soil texture class	Percent of cropland acres	Commercial fertilizer (lb/a)	Manure (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Sum of all losses (lb/a)
Coarse	5.1	13.46	5.51	0.40	1.77	0.28	0.14	2.58
Moderately coarse	10.9	12.46	4.12	0.83	0.64	0.39	0.08	1.94
Medium	51.4	11.86	3.08	1.79	0.22	0.49	0.04	2.55
Moderately fine	6.0	9.00	1.56	1.77	0.24	0.56	0.04	2.60
Fine	26.2	10.89	2.60	1.39	0.32	0.38	0.03	2.12
Organic	0.4	15.89	6.37	6.33	0.08	6.66	0.12	13.20
Other	0.0	10.19	6.09	0.24	0.10	0.35	0.42	1.12
All	100	11.60	3.12	1.53	0.37	0.47	0.05	2.42

Table 59 Sources of phosphorus applied and estimates of phosphorus loss (elemental P)–by hydrologic soil group (average annual values)

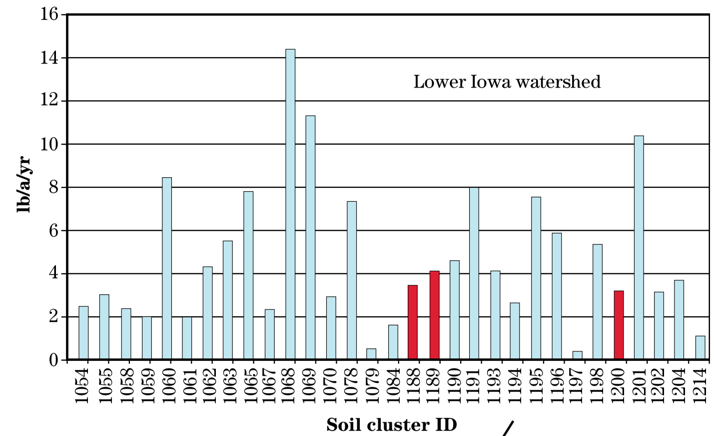
Soil hydrologic soil group	Percent of cropland acres	Commercial fertilizer (lb/a)	Manure (lb/a)	Lost with waterborne sediment (lb/a)	Lost with windborne sediment (lb/a)	Dissolved in surface water runoff (lb/a)	Dissolved in leachate (lb/a)	Sum of all losses (lb/a)
A	3.8	12.56	4.87	0.43	1.74	0.43	0.15	2.42
B	55.5	11.77	3.34	1.31	0.39	0.34	0.04	2.07
C	25.7	12.28	3.04	2.03	0.16	0.63	0.05	2.85
D	15.1	9.55	1.97	1.73	0.30	0.70	0.04	2.66
All	100.0	11.60	3.12	1.53	0.37	0.47	0.05	2.37

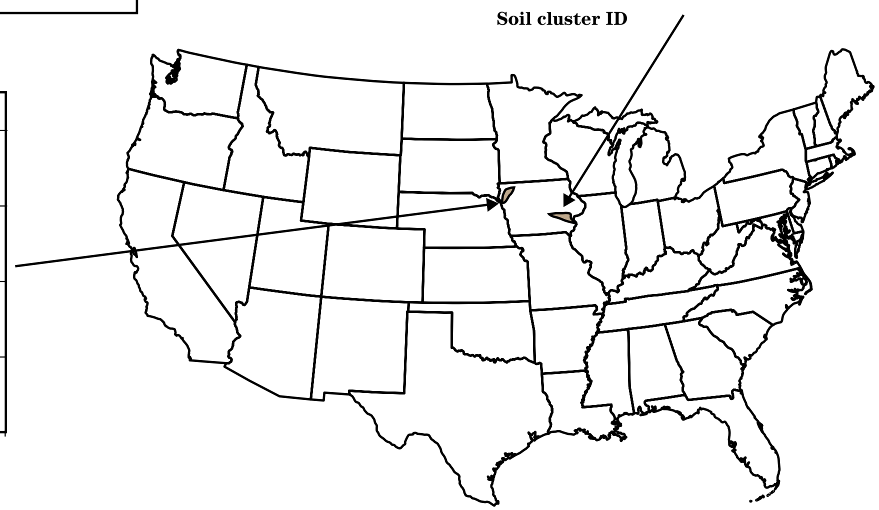
* Excluding organic soils.

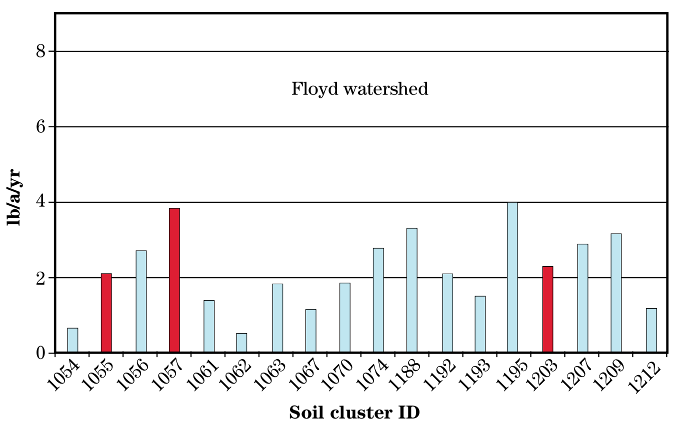
Figure 31 Variability in phosphorus loss estimates (sum of all loss pathways) within two IA watersheds

Soil cluster	Representative soil	Texture group	Hydrologic soil group
1054	Fairhaven	Medium	B
1055	Kossuth	Moderately fine	B
1056	Alton	Moderately fine	C
1057	Galva	Moderately fine	B
1058	Hoopeston	Moderately coarse	B
1059	Coland	Moderately fine	B
1060	Tama	Medium	B
1061	Coppock	Medium	B
1062	Shelby	Moderately fine	B
1063	Turlin	Medium	B
1065	Fayette	Medium	B
1067	Nodaway	Medium	B
1068	Gara	Medium	C
1069	Lindley	Medium	C
1070	Colo	Moderately fine	B
1074	Ida	Medium	B
1078	Adair	Moderately fine	C
1079	Lamont	Moderately coarse	B
1084	Dickinson	Moderately coarse	B
1188	Ely	Medium	B

Soil cluster	Representative soil	Texture group	Hydrologic soil group
1189	Lagoda	Medium	B
1190	Sharpsburg	Moderately fine	B
1191	Adair	Medium	C
1192	Kenyon	Medium	B
1193	Marshall	Moderately fine	B
1194	Sparta	Coarse	A
1195	Huntsville	Medium	B
1196	Downs	Medium	B
1197	Village	Medium	B
1198	Lineville	Medium	C
1200	Humeston	Medium	C
1201	Lamoni	Fine	C
1202	Wabash	Moderately fine	D
1203	Terril	Medium	B
1204	Floyd	Medium	B
1207	Monona	Medium	B
1209	Racine	Medium	B
1212	Spicer	Moderately fine	B
1214	Chelsea	Coarse	A







Note: Phosphorus loss is reported here as elemental phosphorus.

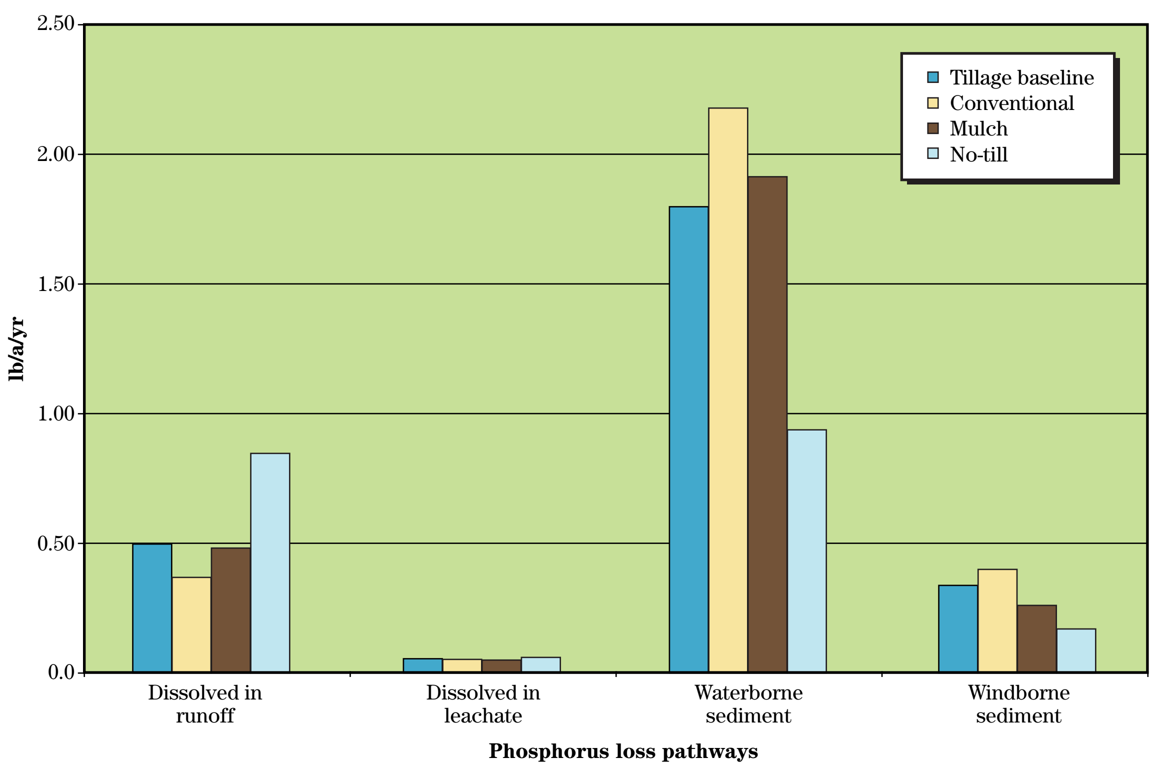
age, and no-till—were present within a URU was used as the domain for examining the effects of tillage.

For the 208 million acres in the tillage comparison subset, the tillage-effects baseline phosphorus loss (sum of all loss pathways) averaged 2.6 pounds per acre per year (table 60), which is nearly the same as the estimate for the full set of NRI sample points included in the study. Model simulation results showed that phosphorus loss summed over all loss pathways would have averaged 3.0 pounds per acre per year if conventional tillage had been used on all acres, indicating that the tillage practices currently in use have reduced phosphorus loss by 13 percent. As shown for sediment loss, phosphorus loss estimates for mulch tillage were similar to the tillage-effects baseline. Phosphorus loss estimates assuming mulch tillage was used on all acres averaged about 10 percent less than if conventional tillage had been used on all acres. Simulation of full implementation of no-till resulted in an average phosphorus loss of 2.0 pounds per acre per year, a decrease of about 0.6 pounds per acre, on average. Full implementation of no-till would have the greatest effect in the Northeast region.

The effect of tillage on phosphorus loss estimates varied by crop (table 60). The largest reductions in phosphorus loss for full implementation of mulch tillage compared to the baseline were for barley, spring wheat, and oats. With full implementation of no-till, phosphorus loss reductions of more than 1 pound per acre, on average, would be obtained for sorghum and corn silage.

The effect of tillage on average phosphorus loss estimates for all acres in the tillage-effects domain is shown in figure 32. For phosphorus dissolved in surface water runoff, no-till losses were actually greater

Figure 32 Effects of tillage practices on phosphorus loss estimates–by loss pathway



Note: Phosphorus loss is reported here as elemental phosphorus.

Table 60 Effects of tillage practices on estimates of phosphorus loss, sum of all loss pathways (lb/a/yr)

		Phosphorus loss, all pathways				Change relative to the tillage-effects baseline			Change relative to conventional tillage	
	Acres in tillage comparison subset (1,000s)	Tillage-effects baseline	Conventional tillage	Mulch tillage	No-till	Conventional tillage	Mulch tillage	No-till	Mulch tillage	No-till
By region										
Northeast	6,034	7.5	8.3	7.6	5.3	0.8	0.1	-2.2	-0.7	-3.0
Northern Great Plains	56,551	3.7	4.1	4.0	3.3	0.4	0.3	-0.4	-0.1	-0.8
South Central	24,879	2.8	3.1	3.1	2.3	0.3	0.3	-0.5	0.0	-0.8
Southeast	4,442	3.1	3.5	3.2	2.4	0.4	0.2	-0.7	-0.2	-1.1
Southern Great Plains	17,746	1.6	1.8	1.3	1.0	0.2	-0.2	-0.6	-0.5	-0.8
Upper Midwest	96,330	1.6	1.8	1.4	1.0	0.2	-0.2	-0.7	-0.4	-0.8
West	1,661	1.5	1.6	1.4	1.3	0.1	-0.1	-0.3	-0.2	-0.3
By crop										
Barley	3,256	1.3	1.4	0.8	0.7	0.1	-0.5	-0.6	-0.7	-0.7
Corn	71,016	4.5	4.9	4.6	3.5	0.4	0.1	-0.9	-0.3	-1.3
Corn silage	4,082	9.1	9.5	9.4	7.0	0.4	0.3	-2.0	-0.1	-2.5
Oats	2,078	2.1	2.3	1.7	1.5	0.2	-0.4	-0.6	-0.6	-0.8
Spring wheat	18,074	1.1	1.3	0.6	0.5	0.2	-0.5	-0.6	-0.7	-0.8
Sorghum	7,697	3.2	3.4	3.1	2.0	0.3	0.0	-1.2	-0.3	-1.5
Soybeans	62,967	1.7	2.1	1.9	1.1	0.4	0.2	-0.5	-0.2	-0.9
Winter wheat	38,473	1.0	1.1	0.8	0.8	0.1	-0.2	-0.2	-0.3	-0.3
All crops and regions	207,642	2.6	3.0	2.7	2.0	0.4	0.1	-0.6	-0.3	-1.0

Note: The subset used for this analysis includes only those URU where all three tillage systems were present. The tillage-effects baseline results represent the mix of tillage systems as reported in the Crop Residue Management Survey for 2000 (CTIC 2001). Tillage-effects baseline results reported in this table will differ from results reported in table 55 because they represent only about 70 percent of the acres in the full database. Results presented for each tillage system represent phosphorus loss estimates as if all acres had been modeled using a single tillage system.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

than the other tillage scenarios. This increase in dissolved phosphorus loss with no-till is more than offset, however, by the decreases in waterborne sediment.

Effects of three conservation practices on phosphorus loss

In addition to tillage effects, three conservation practices—contour farming, stripcropping, and terraces—were shown to have a significant influence on sediment loss and a positive—but more modest—influence on nitrogen loss estimates (tables 25 and 42). As shown for tillage practices, these three conservation practices were much more effective in reducing phosphorus loss than in reducing nitrogen loss. For comparison to the results for the model runs that included conservation practices, an additional set of model runs were conducted after adjusting model settings to represent no practices. The difference between the no-practices scenario and the conservation-practices baseline scenario (consisting of the original model runs for NRI sample points with conservation practices) is used here to assess the extent to which conservation practices reduced the phosphorus loss estimates (table 13 and related discussion).

For the 31.7 million acres modeled with conservation practices, phosphorus loss estimates (sum of all loss pathways) averaged 2.5 pounds per acre per year (table 61), which was close to the estimate for the full set of NRI sample points included in the study. If conservation practices had not been accounted for in the model simulations, phosphorus loss estimates on these acres would have averaged 3.4 pounds per acre per year, representing a reduction in phosphorus loss of about 1 pound per acre. These model simulations suggest, therefore, that the conservation practices reported by the NRI reduce phosphorus loss by about 28 percent, on average, for acres with one or more of the three practices.

The bulk of the reductions in phosphorus loss resulted from reductions in waterborne sediment in all but the Southern Great Plains region, where reductions in windborne sediment were also important. There was little difference in phosphorus dissolved in surface water runoff between the two scenarios. However, phosphorus dissolved in leachate was about 0.3 pounds per acre higher for the conservation-effects baseline scenario than for the no-practices scenario, indicating a trade-off between sediment and phosphorus reduction from erosion control practices and a slight increase in phosphorus leaching.

As observed for nitrogen loss, the largest reductions in phosphorus loss occurred for contour farming alone (1.4 lb/a/yr) and contour farming in combination with stripcropping (2.7 lb/a/yr). The most prevalent practice set—contour farming and terraces—reduced phosphorus loss estimates about 1.0 pounds per acre per year. Terraces only or stripcropping only resulted in the smallest reductions—less than 0.4 pounds per acre per year on average.

The effects of conservation practices varied considerably by region as shown in table 61. The largest phosphorus loss reductions occurred in the Northeast and Upper Midwest regions, which were also the regions with the highest sediment loss reductions attributable to the three conservation practices. Phosphorus loss reductions for acres with one or more of the three conservation practices in these two regions were about 2.0 pounds per acre per year, on average. The largest reduction in phosphorus loss was for the combination of contour farming and stripcropping in the Northeast region, which reduced phosphorus loss by 3 pounds per acre per year—37 percent.

Assessment of critical acres for phosphorus loss

Two of the phosphorus loss pathways are used to identify critical acres for phosphorus loss:

- phosphorus lost with waterborne sediment
- phosphorus dissolved in surface water runoff

Phosphorus lost with windborne sediment is well represented by critical acres identified for wind erosion. Phosphorus dissolved in leachate had levels too low to be useful as a criterion for identifying critical acres.

Specific regions of the country have been shown in this study to have a much higher potential for phosphorus loss from these two loss pathways than other areas of the country. Moreover, as shown in maps 29 and 31 and in the example for the two Iowa watersheds, phosphorus loss estimates often varied considerably within relatively small geographic areas. Estimates of the average phosphorus loss by region and by crops within regions mask much of this under-

Table 61 Effects of three conservation practices on estimates of phosphorus loss, sum of all loss pathways (lb/a/yr)

				Phosphorus loss			
Region	**Conservation practices**	**Number of NRI sample points**	**Acres (1,000s)**	**Conservation-practices aseline scenario**	**No-practices scenario**	**Difference**	**Percent difference relative to no-practices scenario**
All regions	Contour farming only	3,728	5,965	4.1	5.6	-1.4	-26
	Contour farming and stripcropping	1,183	1,764	3.7	6.4	-2.7	-42
	Contour farming and terraces	7,883	14,728	2.0	3.0	-1.0	-34
	Contour farming, stripcropping, and terraces	31	64	2.1	3.2	-1.1	-35
	Stripcropping only	1,308	2,930	2.0	2.4	-0.4	-18
	Terraces only	3,268	6,285	1.9	2.1	-0.2	-8
	All practices	17,401	31,737	2.5	3.4	-1.0	-28
Northeast	Contour farming only	338	485	7.0	8.8	-1.7	-20
	Contour farming and stripcropping	454	595	5.2	8.2	-3.0	-37
	Stripcropping only	423	526	6.3	8.2	-1.9	-23
	All practices	1,215	1,606	6.1	8.4	-2.3	-27
Southeast	Contour farming only	275	456	4.6	5.0	-0.4	-9
	Contour farming and terraces	132	234	2.4	2.5	0.0	-1
	Terraces only	52	92	3.2	2.7	0.5	20
	All practices	459	782	3.8	4.0	-0.2	-5
South Central	Contour farming only	110	172	5.0	5.8	-0.8	-14
	Contour farming and terraces	1,173	1,963	2.3	3.2	-0.8	-26
	Terraces only	1,169	1,974	2.5	2.6	-0.1	-3
	All practices	2,452	4,109	2.5	3.0	-0.5	-16
Upper Midwest	Contour farming only	2,625	4,239	4.0	5.7	-1.7	-30
	Contour farming and stripcropping	702	1,106	3.0	5.6	-2.6	-46
	Contour farming and terraces	3,621	5,293	2.4	4.6	-2.2	-47
	Stripcropping only	156	231	3.9	5.1	-1.1	-23
	Terraces only	637	985	3.0	3.6	-0.6	-18
	All practices	7,741	11,853	3.1	5.0	-1.9	-38

Table 61 Effects of three conservation practices on estimates of phosphorus loss, sum of all loss pathways (lb/a/yr)—Continued

Region	Conservation practices	Number of NRI sample points	Acres (1,000s)	Phosphorus loss: Conservation-practices aseline scenario	No-practices scenario	Difference	Percent difference relative to no-practices scenario
Northern Great Plains	Contour farming only	268	365	1.9	2.6	-0.7	-26
	Contour farming and terraces	1,370	3,553	1.0	1.2	-0.3	-23
	Stripcropping only	602	1,945	0.4	0.4	0.0	-5
	Terraces only	213	495	1.1	1.3	-0.2	-12
	All practices	2,453	6,357	0.8	1.1	-0.2	-20
Southern Great Plains	Contour farming only	104	235	3.0	3.0	0.0	-2
	Contour farming and terraces	1,585	3,681	4.0	3.7	0.3	9
	Stripcropping only	80	149	2.1	2.4	-0.3	-13
	Terraces only	1,122	2,677	3.0	2.8	0.2	6
	All practices	2,891	6,743	1.2	1.3	-0.1	-6
West	Terraces only	72	58	1.8	2.0	-0.2	-10

Note: Results for conservation practices and combinations of practices based on less than 20 NRI sample points are not shown in the regional breakdowns, but these data are included in the aggregated results for all regions.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

lying variability. Tables 62 and 63 demonstrate the extent of both regional and local variability by presenting the percentiles for each of the phosphorus loss pathways for each region.

For phosphorus lost with waterborne sediment, the mean of the distribution exceeded the median for all regions (table 62), indicating that the bulk of the phosphorus loss estimates for this pathway is below the average and that there is a minority of sample points with very high loss estimates. This disproportionality was pronounced for 2 regions—the Northeast and West. In the West region, the mean exceeded the 75th percentile. In most regions, the 90th percentile loss estimate was twice as high as the average loss estimate, and over three times higher in the Northeast region.

All regions exhibited disproportionality for phosphorus dissolved in surface water runoff (table 63), but overall the disproportinality was less than for phosphorus lost with waterborne sediment. In the Southeast region, however, the disproportionality was strong as indicated by the mean being nearly equal to the 75th percentile.

Five categories of critical acres for phosphorus lost with waterborne sediment, representing different degrees of severity, are defined on the basis of national level results.

- acres where phosphorus loss is above the 95th percentile for all acres included in the study (5.550 lb/a/yr)
- acres where phosphorus loss is above the 90th percentile for all acres included in the study (3.633 lb/a/yr)
- acres where phosphorus loss is above the 85th percentile for all acres included in the study (2.781 lb/a/yr)
- acres where phosphorus loss is above the 80th percentile for all acres included in the study (2.165 lb/a/yr)
- acres where phosphorus loss is above the 75th percentile for all acres included in the study (1.798 lb/a/yr)

Five categories of critical acres for phosphorus dissolved in surface water runoff were defined in a similar manner:

- acres where phosphorus loss is above the 95th percentile for all acres included in the study (1.274 lb/a/yr)
- acres where phosphorus loss is above the 90th percentile for all acres included in the study (1.000 lb/a/yr)
- acres where phosphorus loss is above the 85th percentile for all acres included in the study (0.827 lb/a/yr)
- acres where phosphorus loss is above the 80th percentile for all acres included in the study (0.712 lb/a/yr)
- acres where phosphorus loss is above the 75th percentile for all acres included in the study (0.621 lb/a/yr)

The regional representation of critical acres is shown in tables 64 and 65 for each of the five categories. Over 90 percent of the acres with per-acre estimates of phosphorus lost with waterborne sediment in the top 5 percent were in three regions—the Upper Midwest region (55% of critical acres), South Central region (18%), and Northeast region (20%). These are the same three regions with the majority of the critical acres for sediment loss and for nitrogen lost with waterborne sediment. For phosphorus dissolved in surface water runoff, the South Central (50%) and Upper Midwest (23%) regions had the majority of acres in the top 5 percent. In the Northeast region, half of the cropland acres were designated as critical acres in the top 25 percent for phosphorus dissolved in surface water runoff.

These critical acres accounted for the bulk of the 69,967 tons per year of phosphorus dissolved in surface water runoff and the 227,863 tons per year of phosphorus lost with waterborne sediment. The 95th percentile category, representing the 5 percent of acres with the highest per-acre losses, accounted for 24 percent of the total tons of phosphorus dissolved in surface water runoff and 31 percent of the total tons of phosphorus lost with waterborne sediment. The 25

percent of acres with the highest per-acre losses accounted for 61 percent of the total tons of phosphorus dissolved in surface water runoff and 71 percent of the total tons of phosphorus lost with waterborne sediment. Following is the percentile breakdown:

Percentile	Percent of total tons of phosphorus dissolved in surface water runoff	Percent of total tons of phosphorus lost with waterborne sediment
95th	24.3	31.2
90th	36.3	45.8
85th	46.0	56.2
80th	54.2	64.2
75th	61.3	70.6

Table 62 Percentiles of phosphorus lost with waterborne sediment (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	3.429	0.000	0.000	0.005	0.746	4.715	10.899	15.531
Northern Great Plains	72,396,500	36,035	0.675	0.002	0.022	0.137	0.516	0.875	1.621	2.187
South Central	45,349,900	27,465	1.853	0.004	0.129	0.576	1.264	2.349	4.058	6.033
Southeast	13,394,400	8,955	1.615	<.001	0.004	0.122	0.672	1.677	3.471	6.579
Southern Great Plains	32,096,000	14,495	0.521	0.025	0.053	0.172	0.334	0.679	1.192	1.674
Upper Midwest	112,580,900	74,691	2.076	<.001	0.026	0.562	1.310	2.719	4.807	6.864
West	9,018,400	5,644	0.446	0.000	0.000	0.010	0.083	0.355	1.192	1.737
All regions	298,478,000	178,567	1.527	<.001	0.011	0.260	0.758	1.798	3.633	5.550

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

Table 63 Percentiles of phosphorus dissolved in surface water runoff (lb/a/yr)

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	0.705	0.113	0.152	0.218	0.627	1.013	1.360	1.663
Northern Great Plains	72,396,500	36,035	0.155	0.019	0.025	0.061	0.116	0.205	0.330	0.418
South Central	45,349,900	27,465	0.806	0.159	0.219	0.340	0.589	0.969	1.773	2.321
Southeast	13,394,400	8,955	0.873	0.098	0.130	0.227	0.446	0.865	1.548	2.066
Southern Great Plains	32,096,000	14,495	0.123	0.011	0.017	0.034	0.068	0.147	0.322	0.448
Upper Midwest	112,580,900	74,691	0.564	0.092	0.136	0.297	0.496	0.723	1.012	1.192
West	9,018,400	5,644	0.375	0.029	0.052	0.090	0.208	0.427	0.952	1.235
All regions	298,478,000	178,567	0.469	0.028	0.051	0.119	0.310	0.621	1.000	1.274

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower loss estimates.
Note: Phosphorus loss is reported here as elemental phosphorus; to convert to phosphate fertilizer equivalent (P_2O_5), multiply by 2.29.

Table 64 Critical acres for phosphorus lost with waterborne sediment

		Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 25% nationally	
Region	**Acres**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**
Northeast	13,641,900	3,017,000	20.2	4,012,600	13.4	4,656,800	10.4	5,330,600	8.9	5,562,700	7.5
Northern Great Plains	72,396,500	90,700	0.6	622,800	2.1	1,668,200	3.7	3,666,800	6.1	4,963,400	6.7
South Central	45,349,900	2,658,200	17.8	5,497,800	18.4	8,741,700	19.5	12,411,000	20.8	15,673,300	21.0
Southeast	13,394,400	865,900	5.8	1,246,200	4.2	1,663,300	3.7	2,333,200	3.9	3,114,700	4.2
Southern Great Plains	32,096,000	12,300	0.1	147,800	0.5	247,500	0.6	812,500	1.4	1,290,000	1.7
Upper Midwest	112,580,900	8,215,000	55.0	18,176,300	60.9	27,562,100	61.6	34,841,100	58.4	43,648,700	58.5
West	9,018,400	63,800	0.4	145,300	0.5	225,400	0.5	298,800	0.5	365,100	0.5
All regions	298,478,000	14,922,900	100.0	29,848,800	100.0	44,765,000	100.0	59,694,000	100.0	74,617,900	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 62. Other columns correspond to table 62 in a similar manner.

Table 65 Critical acres for phosphorus dissolved in surface water runoff

		Per-acre loss in top 5% nationally		Per-acre loss in top 10% nationally		Per-acre loss in top 15% nationally		Per-acre loss in top 20% nationally		Per-acre loss in top 2% nationally	
Region	**Acres**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**
Northeast	13,641,900	1,674,300	11.2	3,575,700	12.0	5,314,500	11.9	6,124,400	10.3	6,849,500	9.2
Northern Great Plains	72,396,500	36,300	0.2	71,600	0.2	187,600	0.4	394,700	0.7	1,059,400	1.4
South Central	45,349,900	7,381,400	49.5	10,851,300	36.4	14,308,400	32.0	18,031,600	30.2	21,559,900	28.9
Southeast	13,394,400	1,886,700	12.6	2,684,700	9.0	3,462,300	7.7	4,361,600	7.3	4,945,800	6.6
Southern Great Plains	32,096,000	33,700	0.2	85,000	0.3	194,100	0.4	288,700	0.5	451,000	0.6
Upper Midwest	112,580,900	3,474,100	23.3	11,750,900	39.4	20,174,300	45.1	29,226,500	49.0	38,262,900	51.3
West	9,018,400	429,900	2.9	819,400	2.7	1,058,500	2.4	1,249,400	2.1	1,490,100	2.0
All regions	298,478,000	14,916,400	100.0	29,838,600	100.0	44,699,700	100.0	59,676,900	100.0	74,618,600	100.0

Note: The top 5 percent corresponds to the 95th percentile in table 63. Other columns correspond to table 63 in a similar manner.

Soil organic carbon and change in soil organic carbon

Modeling the carbon cycle

Plants gather and package energy from the sun through photosynthesis, the process in which plants trap light energy and convert it to chemical energy. Through photosynthesis, plants take in carbon dioxide (CO_2) from the atmosphere and water from the soil, split off the oxygen atom from water, release oxygen gas back to the atmosphere, and combine the carbon atom with other carbon atoms and minerals, including nitrogen and phosphorus, to produce plant tissue and crop yield.

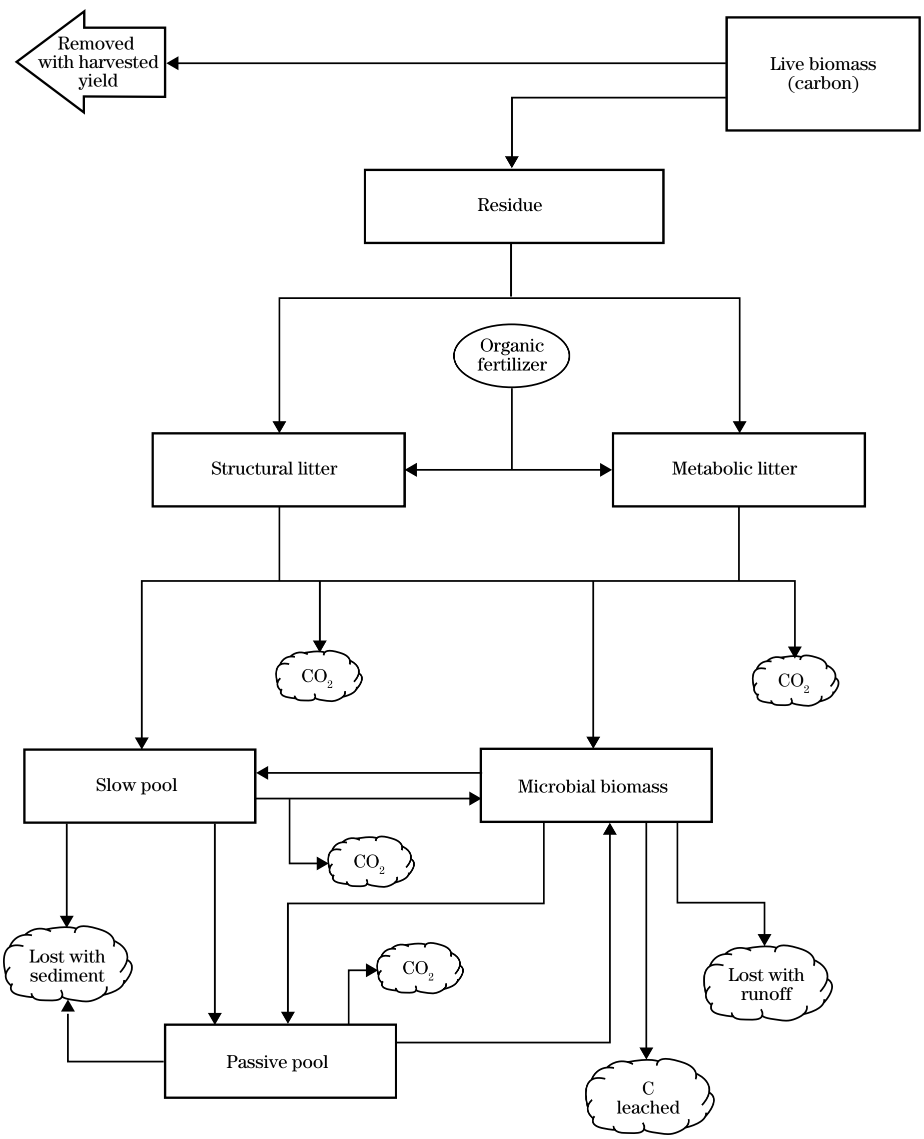
Part of the plant is removed from the field when the crop is harvested. Other plant material on the surface remains in the field as crop residue. Crop residue includes plant stems, leaves, and roots. Over time the plant material decomposes. Some molecules, those most readily decomposable, are quickly incorporated into microorganisms and other soil biota that use it as an energy source. Other plant materials, made of less easily decomposed materials such as lignin, become structural or metabolic litter. As the litter decomposes into compounds like CO_2 and NH_4, its identity as plant material disappears. Some molecules remain resistant to decomposition for thousands of years. In some systems used by soil scientists to describe soil organic matter, including the EPIC model, the most highly resistant fractions of organic material are classified as passive humus. Other materials, resistant for up to 20 years or so, are classified as slow humus. Fractions that decompose faster are part of the biomass, structural litter, or metabolic litter and are often labeled as active or labile organic material. All non-living organic material in the soil not readily identifiable as plant parts comprise that soil component called soil organic matter. The buildup of soil organic matter in the soil results in enhanced soil quality.

EPIC simulates dynamic carbon processes using carbon routines conceptually similar to those in the Century model (Izaurralde et al. 2001; Izaurralde et al. 2005). In EPIC, carbon processes are coupled to the hydrology, erosion, soil temperature, plant growth, nutrient cycling, and tillage components (fig. 33). EPIC tracks the residue and calculates the mass of carbon in the soil. The organic material is apportioned into any of five pools: metabolic litter, structural litter, microbial biomass, slow humus, and passive humus depending on its inherent decomposition rate as estimated by the lignin composition. The model tracks and reapportions the pools over time using a daily mass balance. Decomposition rates are influenced by various environmental factors including climate and soil characteristics. EPIC represents these factors using transformation rate controls exerted by the soil temperature and soil water equations. Tillage and other management operations are simulated to represent affects on decomposition rates. EPIC includes leaching equations that move soluble carbon down through the soil profile. Other equations capture the effects of soil texture on the stabilization of soil organic matter.

EPIC calculates soil organic carbon by summing the products of layer thickness, bulk density, and proportion of soil organic carbon in the soil for each layer in the soil profile. Soil organic carbon includes the microbial biomass and slow and passive humus pools, but not residue or litter. The calculation is very sensitive to the bulk density estimate, as there are large differences in the mass per volume between organic material and mineral material. Considering the soil in the example below, the multiple of columns 1, 2, and 3 times 100 results in metric tons of soil organic carbon per 100 square meters for each soil layer. This is then converted to metric tons per hectare for each layer by multiplying by 100 square meters per hectare (col. 5) and then converted to tons per acre by multiplying by the product of 1.1023 metric tons per ton and 0.4047 hectares per acre (col. 6). Total soil organic carbon for the soil profile is obtained by summing over the layers. In the following example, soil organic carbon in the soil profile is 58.7 tons per hectare, or 26.2 tons per acre:

Soil layer	Layer thickness (m)	Bulk density (metric ton/m^3)	Proportion of soil organic carbon	Metric tons of soil organic carbon per 100 square meters	Metric tons of soil organic carbon per hectare	Tons of soil organic carbon per acre
	Col. 1	**Col. 2**	**Col. 3**	**Col. 4**	**Col. 5**	**Col. 6**
1	0.01	1.56	0.0231	0.036	3.604	1.608
1	0.29	1.56	0.0074	0.335	33.478	14.934
2	0.16	1.44	0.0025	0.058	5.760	2.540
3	0.73	1.55	0.0014	0.158	15.841	7.067

Figure 33 Carbon cycle as modeled in EPIC



Model simulation results for soil organic carbon

Soil organic carbon

In these model simulations, the initial soil organic carbon is the soil organic carbon input derived from the soil properties database associated with the representative soil for each soil cluster. As described earlier in this report, a 40-year simulation was conducted with the first 10 years serving as the equilibration period for the model to adjust to the various default starting values, including the initial value for soil organic carbon. Annual model output was used for reporting beginning with the 11th year of the simulation and ending with the 40th year of the simulation, providing 30 annual estimates of soil organic carbon. Year 1 results correspond to the 11th year of the simulation, and year 30 results correspond to the last year. Over this simulation period, soil organic carbon changes depending on climatic factors, erosion rates, amount of crop residue generated each year, annual organic carbon additions such as manure application, and tillage intensity. The same crop was grown in each year of the simulation with the same management activities each year; crop rotations were not simulated. Weather was simulated using a weather generator; resulting estimates, therefore, do not represent any specific historical time period. Soil organic carbon estimates presented in this report are calculated as the annual average for the 30-year period.

For the 15 specific crops included in the study, model simulations estimated an average of 58 tons of soil organic carbon per cropland acre (table 66). The largest amount of soil organic carbon associated with cropland acres was in the Upper Midwest region, which also had the highest per-acre amount—71 tons per cropland acre on average. The lowest per-acre soil organic carbon levels were in the Southern Great Plains and South Central regions, averaging 43 and 44 tons per acre, respectively. The soil organic carbon content of cropland soils in the West and the Southeast regions was, on average, only slightly higher (table 66).

The spatial distribution of soil organic carbon on a per-acre basis is shown in map 35 and as total tons of soil organic carbon in map 36. It is clear from map 35 that soil organic carbon levels vary considerably among cropland acres. Cropland with the highest organic carbon content—including soils in the organic soil texture class—are shown in the highest category (dark brown colored areas). These acres have an average soil organic carbon content of over 150 tons per acre and represent about 3 percent of the cropland acres included in the study. The few acres that have organic carbon levels this high tend to be concentrated in Minnesota, Iowa, eastern Wisconsin, northern Indiana, and eastern North Carolina. Most cropland acres with soil organic carbon levels averaging 100 to 150 tons per acre are concentrated in Iowa and Minnesota, and represent about 7 percent of the cropland acres. Cropland acres with the lowest soil organic carbon levels—less than 25 tons per acre and representing about 14 percent of the acres—primarily are scattered throughout the southern half of the country.

Soil organic carbon levels also varied by crop within regions, as shown in table 66**.** Legume hay consistently had the highest or among the highest soil organic carbon levels in every region. Cotton and peanuts had the lowest soil organic carbon levels in regions where those crops were grown. The highest soil organic carbon level when averaged by crop within region was for spring wheat in the Upper Midwest region—123 tons per acre. The lowest was for cotton in the West—16 tons of soil organic carbon per acre.

Soil organic carbon levels and soil texture are inter-related in these model simulations, as shown in figure 34 and table 67. Soil organic carbon content was highest for fine textured soils and decreased as the soils became coarser in texture, with the exception of the soils in hydrologic soil group D. Coarse soils in hydrologic soil group D had among the highest levels of soil organic carbon. Organic soils, which represent less than 0.5 percent of cropland acres, averaged over 600 tons per acre of soil organic carbon.

Change in soil organic carbon

Under the assumptions of the model simulation, nearly three-fourths of the cropland acres lost soil organic carbon over the 30 years (table 68). However, many of these losses were very small. About half of the acres losing carbon in these model simulations lost less than 3 tons per acre over the 30 years, equivalent to only about 0.1 tons per acre per year or less. Gains and losses this small are difficult to detect in an actual farm field setting, and may represent a steady state condition where small carbon gains occur in some years that are mostly offset by small carbon losses in other years.

Table 66 Soil organic carbon estimates–by region and by crop within regions

Region	Crop	Acres (1,000s)	Tons (1,000s)	30-year change in tons (1,000s)	Tons per acre	30-year change in tons per acre	30-year percent change in tons per acre
By region							
Northeast	All crops	13,642	743,013	191,270	54.5	14.0	28.7
Northern Great Plains	All crops	72,397	4,081,437	-94,257	56.4	-1.3	-2.3
South Central	All crops	45,350	2,000,380	4,282	44.1	0.1	0.2
Southeast	All crops	13,394	628,985	8,049	47.0	0.6	1.3
Southern Great Plains	All crops	32,096	1,392,353	-105,340	43.4	-3.3	-7.3
Upper Midwest	All crops	112,581	8,029,824	29,188	71.3	0.3	0.4
West	All crops	9,018	417,195	22,693	46.3	2.5	5.6
All regions	All crops	298,478	17,293,187	55,886	57.9	0.2	0.3
By crop within region*							
Northeast	Corn	2,943	121,919	-10,979	41.4	-3.7	-8.6
	Corn silage	1,482	56,510	-11,401	38.1	-7.7	-18.1
	Grass hay	2,369	115,664	650	48.8	0.3	0.6
	Legume hay	4,052	343,888	223,074	84.9	55.1	89.7
	Oats	362	15,460	-1,916	42.7	-5.3	-11.6
	Soybeans	1,305	46,746	-3,531	35.8	-2.7	-7.2
	Winter wheat	853	30,291	-2,785	35.5	-3.3	-8.8
Northern Great Plains	Barley	3,243	229,224	-3,368	70.7	-1.0	-1.4
	Corn	15,466	784,030	-42,844	50.7	-2.8	-5.3
	Corn silage	810	37,291	-3,888	46.1	-4.8	-9.8
	Grass hay	2,443	149,209	12,607	61.1	5.2	8.8
	Legume hay	6,152	362,445	58,582	58.9	9.5	17.3
	Oats	1,255	70,065	-3,605	55.8	-2.9	-5.0
	Spring wheat	18,916	1,234,053	-47,102	65.2	-2.5	-3.7
	Sorghum	1,595	66,388	-3,567	41.6	-2.2	-5.2
	Soybeans	9,562	611,474	-45,596	64.0	-4.8	-7.1
	Winter wheat	12,748	522,517	-13,319	41.0	-1.0	-2.5
South Central	Corn	5,956	249,374	-10,294	41.9	-1.7	-4.0
	Cotton	5,487	159,940	-27,435	29.1	-5.0	-15.7
	Grass hay	3,347	153,638	3,234	45.9	1.0	2.1
	Legume hay	1,630	153,452	128,389	94.1	78.7	129.0
	Peanuts	880	22,721	-1,952	25.8	-2.2	-8.2
	Rice	3,004	108,803	-14,825	36.2	-4.9	-12.7
	Sorghum	2,729	160,825	-13,890	58.9	-5.1	-8.3
	Soybeans	14,083	580,697	-22,291	41.2	-1.6	-3.8
	Winter wheat	7,896	395,855	-34,709	50.1	-4.4	-8.4

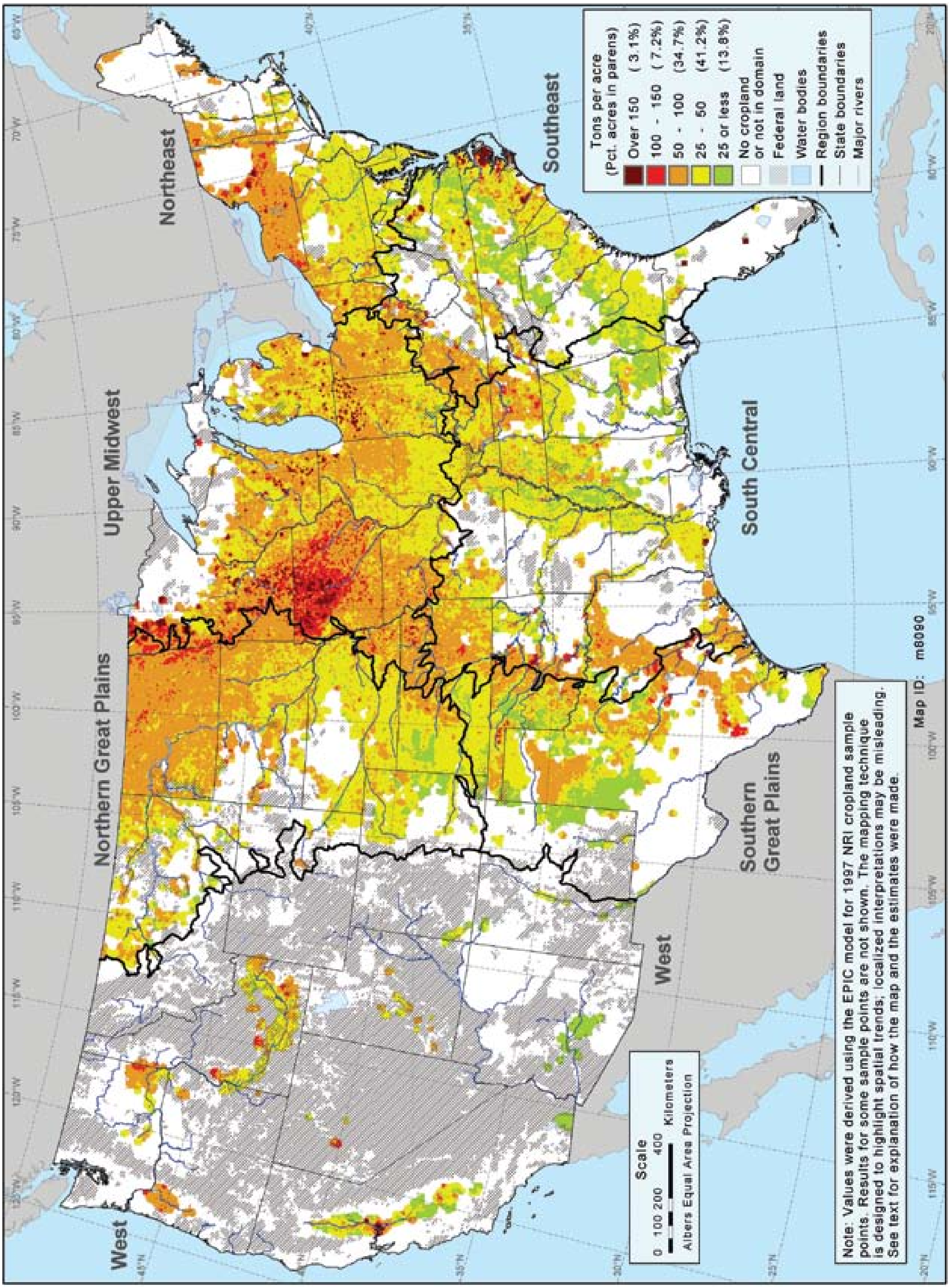
Table 66 Soil organic carbon estimates–by region and by crop within regions—Continued

Region	Crop	Acres (1,000s)	Tons (1,000s)	30-year change in tons (1,000s)	Tons per acre	30-year change in tons per acre	30-year percent change in tons per acre
By crop within region*							
Southeast	Corn	3,028	184,211	-21,771	60.8	-7.2	-11.1
	Corn silage	412	15,624	-1,776	37.9	-4.3	-10.7
	Cotton	2,422	77,859	-14,874	32.1	-6.1	-17.4
	Grass hay	2,000	80,660	77	40.3	<0.1	0.1
	Legume hay	1,183	92,145	73,208	77.9	61.9	120.7
	Peanuts	479	13,708	-1,619	28.6	-3.4	-11.1
	Soybeans	2,419	100,666	-14,570	41.6	-6.0	-13.4
	Winter wheat	1,216	51,716	-8,802	42.5	-7.2	-15.6
Southern Great Plains	Corn	2,665	122,199	-10,379	45.9	-3.9	-8.1
	Cotton	7,316	239,430	-41,400	32.7	-5.7	-15.8
	Legume hay	677	40,861	16,340	60.3	24.1	48.2
	Oats	503	29,756	-2,908	59.1	-5.8	-9.3
	Peanuts	484	9,732	-1,198	20.1	-2.5	-11.5
	Sorghum	4,895	222,676	-22,970	45.5	-4.7	-9.8
	Winter wheat	15,037	702,914	-42,355	46.7	-2.8	-5.8
Upper Midwest	Corn	47,941	3,430,754	-215,962	71.6	-4.5	-6.1
	Corn silage	1,947	104,537	-10,555	53.7	-5.4	-9.6
	Grass hay	4,044	260,068	7,996	64.3	2.0	3.1
	Legume hay	9,233	806,086	484,358	87.3	52.5	80.0
	Oats	1,388	77,389	-8,378	55.8	-6.0	-10.2
	Spring wheat	815	100,110	-5,916	122.8	-7.3	-5.7
	Sorghum	1,604	96,759	-7,479	60.3	-4.7	-7.4
	Soybeans	40,049	2,822,992	-204,019	70.5	-5.1	-6.9
	Winter wheat	5,147	286,890	-7,279	55.7	-1.4	-2.5
West	Barley	958	45,836	-1,891	47.9	-2.0	-4.0
	Corn silage	297	16,695	-1,063	56.2	-3.6	-6.1
	Cotton	1,631	26,687	-2,463	16.4	-1.5	-8.8
	Legume hay	1,847	99,887	38,218	54.1	20.7	46.2
	Potatoes	329	11,036	-841	33.5	-2.6	-7.3
	Rice	599	22,307	-3,982	37.2	-6.6	-16.3
	Spring wheat	772	32,954	-846	42.7	-1.1	-2.5
	Winter wheat	2,118	124,725	-3,201	58.9	-1.5	-2.5

* Estimates for crops with less than 250,000 acres within a region are not shown. However, acres for these minor crops are included in the calculation of the regional estimates.

Note: A 40-year simulation was conducted. The first 10 years served as the equilibration period for the model to adjust to the various default starting values. The 30-year period from which these carbon estimates were derived started on the 11th year of the simulation and ended with the 40th year of the simulation. Tons reported here are the annual average for the 30-year period.

Map 35 Estimated per-acre soil organic carbon



Map 36 Estimated tons of soil organic carbon for cropland acres

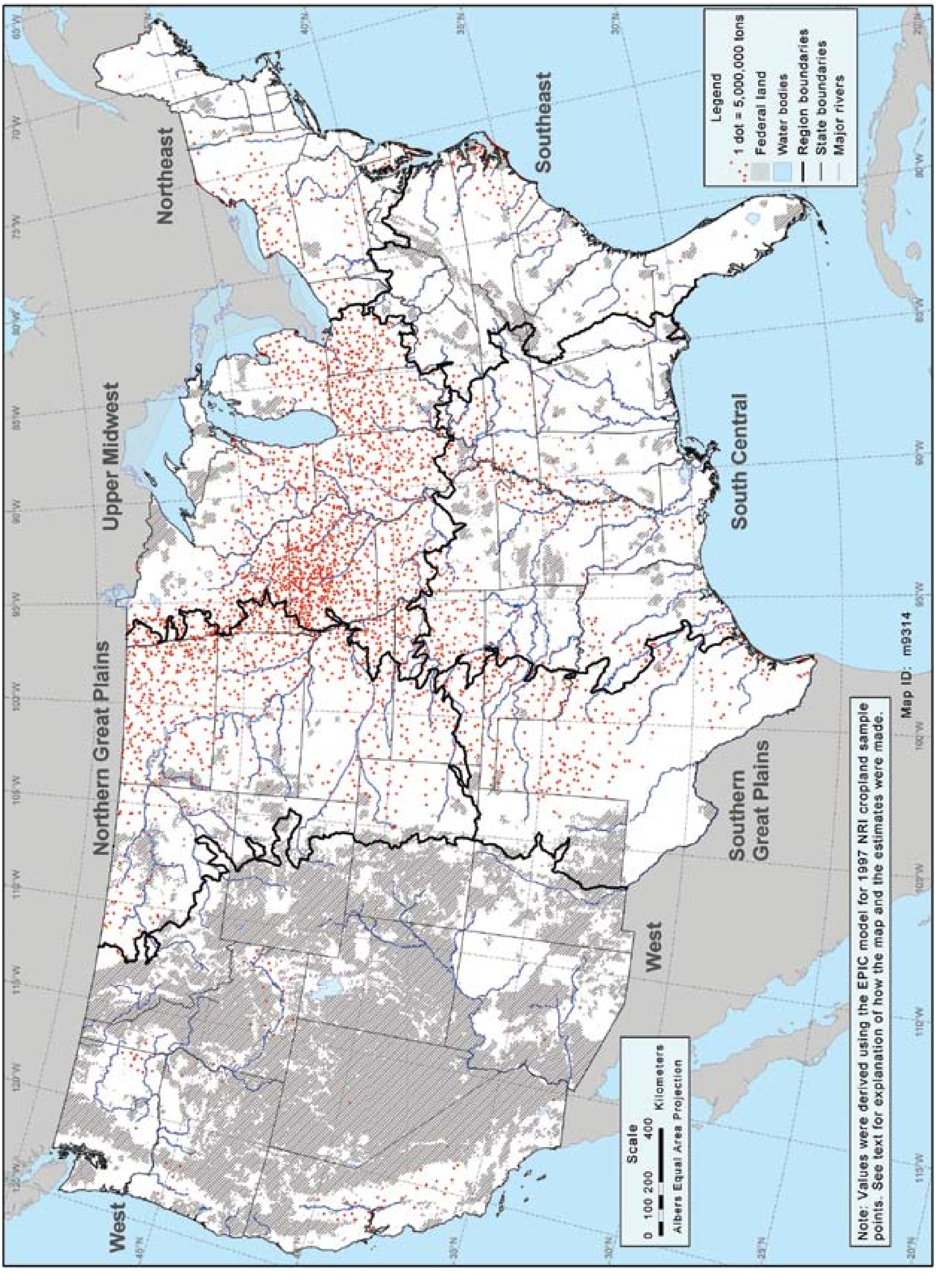


Figure 34 Per-acre soil organic carbon–by soil texture class and hydrologic soil group

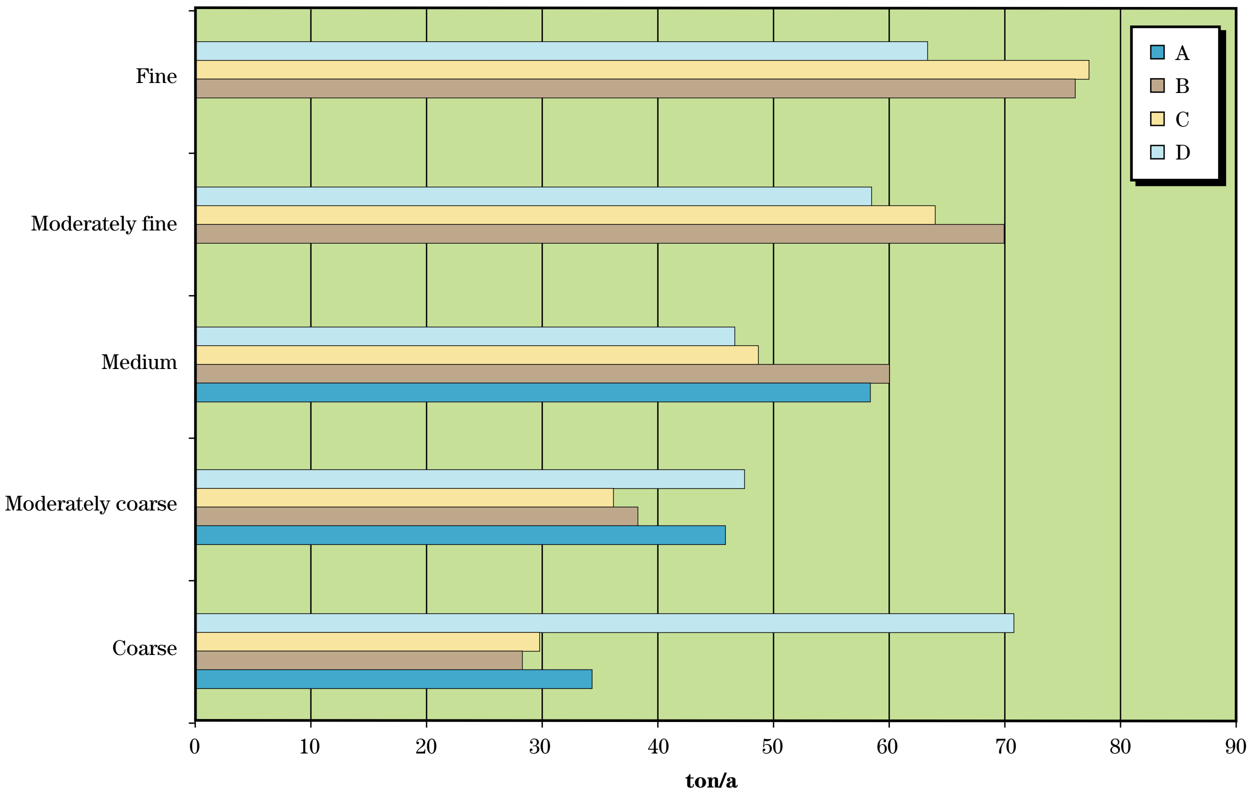


Table 67 Soil organic carbon levels–by soil texture class

Soil texture class	Acres (1,000s)	Percent of total acres	Soil organic carbon (ton/a)	30-year change in soil organic carbon (ton/a)	30-year percent change in soil organic carbon
Coarse	15,152	5.1	32.2	-0.9	-2.7
Moderately coarse	32,452	10.9	38.8	1.4	3.5
Medium	153,484	51.4	55.2	2.3	4.2
Moderately fine	78,249	26.2	66.5	-2.6	-3.8
Fine	17,950	6.0	65.6	-3.5	-5.1
Organic	1,142	0.4	606.8	-52.1	-8.3
Other	49	<0.1	33.0	5.2	16.8
All	298,478	100.0	57.9	0.2	0.3

Table 68 Percentage of acres gaining and losing soil organic carbon over the 30-yr simulation

		Acres loosing soil organic carbon over 30-year period				Acres gaining soil organic carbon over 30-year period			
	Acres (1,000s)	Percent loosing more than 3 tons per acre	Percent loosing 1 to 3 tons per acre	Percent loosing 0 to 1 tons per acre	Sum of percent acres	Percent gaining 0 to 1 tons per acre	Percent gaining 1 to 3 tons per acre	Percent gaining more than 3 tons per acre	Sum of percent acres
Northeast	13,642	31.4	16.9	9.7	58.0	5.4	5.5	31.1	42.0
Northern Great Plains	72,397	27.3	34.0	16.7	78.1	8.6	2.9	10.5	21.9
South Central	45,350	40.4	25.5	9.9	75.8	9.1	8.5	6.6	24.2
Southeast	13,394	38.3	27.0	9.1	74.4	5.4	7.7	12.5	25.6
Southern Great Plains	32,096	52.1	31.3	10.3	93.7	2.7	1.3	2.2	6.3
Upper Midwest	112,581	38.3	20.7	10.4	69.4	12.1	8.4	10.1	30.6
West	9,018	20.3	13.0	15.8	49.1	18.5	13.0	19.5	50.9
All regions	298,478	36.6	25.7	11.9	74.2	9.4	6.3	10.1	25.8

Overall gains in soil organic carbon outweighed overall losses for the acres included in the study. When aggregated over all cropland acres, the change in soil organic carbon averaged only 0.2 tons per acre over the 30-year simulation (table 66). Only the Northern and Southern Great Plains regions had overall soil organic carbon losses on cropland acres (table 66). In the Southern Great Plains region, 94 percent of the cropland acres had decreasing soil organic carbon (table 68), over half of which lost more than 3 tons per acre over the 30-year period. In the Northeast region, the average per-acre soil organic carbon level increased 14 tons per acre over the 30-year simulation, equivalent to about 0.5 tons per acre per year. On average, soil organic carbon gain occurred for only two crops—grass hay and alfalfa hay; other crops had average losses of soil organic carbon in every region (table 66).

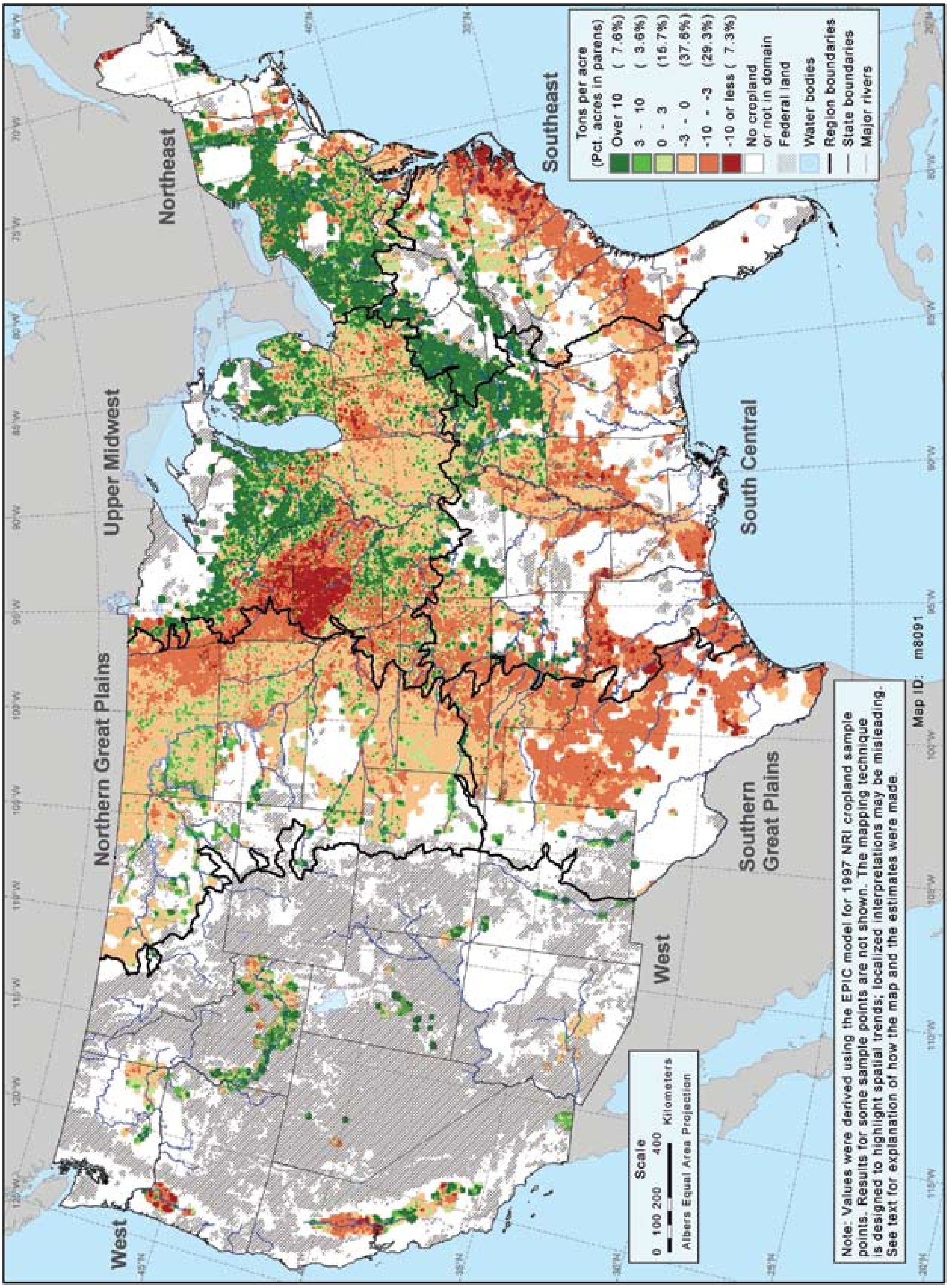
The spatial distribution of the changes in tons per acre of soil organic carbon over the 30-year model simulation is shown in map 37. The green areas on the map had increases in soil organic carbon and the red areas had losses. The lightest red and lightest green colored areas represent very low levels of gains and losses, and probably reflect more of a steady state condition. Broad areas with these low levels of gains and losses occurred in Illinois, Indiana, and western Ohio and in the Northern Great Plains region. The highest losses of soil organic carbon (losses of more than 10 ton/a over the 30-yr period) occurred predominantly in Iowa, southern Minnesota, and eastern North Carolina primarily where soil organic carbon levels were relatively high. These areas represent about 7 percent of the cropland acres included in the study. The spatial distribution and regional differences are largely the result of differences in decomposition rates driven by climate and the crop mix. Higher decomposition rates in the warm humid climates lead to low organic carbon accrual.

The percent change in soil organic carbon is presented in map 38. This map shows the percent change in soil organic carbon relative to the level of soil organic carbon in year 1 of the 30-year model output series. Thus, areas with low soil organic carbon levels but large changes in soil organic carbon are more pronounced in map 38 than in map 37. Soil organic carbon decreased more than 10 percent on about 17 percent of the acres over the 30-year simulation (darkest red color), and increased more than 10 percent on about 10 percent of the acres (darkest green color). Cropland in the southern states generally had the highest losses of soil organic carbon in terms of percent change.

Results in terms of the percent change in soil organic carbon also showed patterns related to soil texture (table 67). Cropland acres with medium and moderately coarse soil textures had, on average, about a 4 percent increase in soil organic carbon over the 30-year simulation, whereas other soil textures were associated with carbon losses, on average. Medium textured soils represent over half of the cropland acres included in the study.

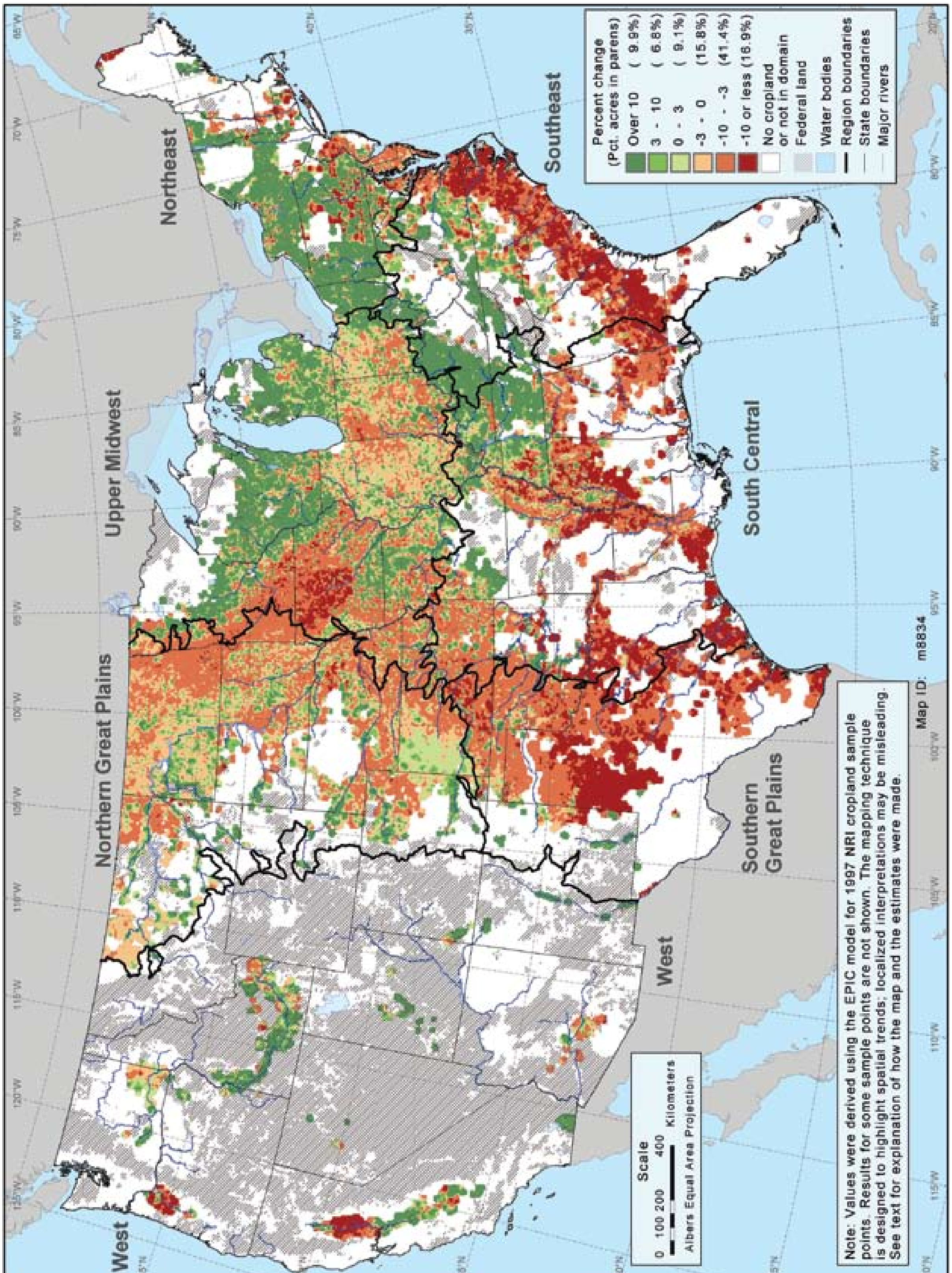
Recent modeling studies using the Century model have reported an accretion in soil organic carbon for common cropping systems in Iowa, Nebraska, and Indiana (Brenner et al. 2001; Brenner et al. 2002; Smith et al. 2002). In contrast, model simulations in this study found that the bulk of the acres in Nebraska and Indiana had very small net losses in soil organic carbon over the 30-year simulation; although, some areas within the states had significant losses while other areas had significant gains (map 37). Most cropland acres in Iowa had significant loss of carbon in this study. Without attempting to make a detailed comparison between the two modeling efforts, there are five main reasons why this study would be expected to estimate higher losses of soil organic carbon than some other studies.

- Estimates in this study included loss of carbon with water and wind erosion. In the EPIC model, carbon may be transported off the field as part of soil eroded by wind and water. The model also includes a routine that leaches soluble organic carbon down through the soil profile. The Century model does not account for this loss from the system, assuming instead that these erosion losses of carbon are merely translocated to other areas and, therefore, do not represent a net loss to the total carbon stock.
- Model simulations in this study did not account for crop rotations or cover crops, as all model runs simulated growth of the same crop over the full simulation time period. Soybeans, for example, produces small amounts of crop residue, whereas corn is a high biomass producing crop with much higher crop residues left in the field under conservation tillage and no-till. Soybeans grown in rotation with corn would have had more carbon added to the soil when averaged



Map 37 30-year change in per-acre soil organic carbon

Map 38 30-year percent change in soil organic carbon (30-yr change/soil organic carbon in year 1)



over the 30-year simulation than continuous soybeans. Other crop rotations beneficial to soil carbon accretion are grasses or legume hay in rotation with row crops and small grains in rotation with row crops.

- Soil organic carbon for some model runs was negatively affected by under-fertilization because the fertilizer application rates were not site-specific. Nitrogen is an essential element for the formation of stable soil organic matter. Average application rates by state and sometimes state combinations were applied to all NRI sample points in those states without regard to soil productivity or differing climatic conditions among the NRI points. Relative to the inherent productivity for the sample point, some received too much fertilizer while others received too little. Thus, soils best positioned to gain soil organic carbon with good agricultural management were restricted because less than optimum fertilizer rates resulted in lower biomass production. Similarly, biomass production could have been restricted because of other management activities, such as tillage, that were also not adjusted to reflect site-specific differences in soils and field conditions.
- Initial soil organic carbon settings are also an important factor in estimating gains and losses. How these data inputs are handled can sometimes explain differences between model outputs in similar studies.
- Site-specific information about drainage was not known, therefore, in the EPIC model simulations, we assumed fields had drainage sufficient to keep the water table to the bottom of the root zone for the entire period. Increased decomposition of soil organic carbon resulting from optimum oxygen conditions is a likely effect of such a global assumption.

Soil organic carbon as an indicator of soil quality

Soil quality in its simplest terms is how well a soil is doing what we want it to do. The definition of soil quality adopted by the Soil Science Society of America is *the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation***.** The definition of soil quality includes two aspects: the inherent properties of soil and the effect of human use and management on the ability of the soil to function. The inherent properties of the soil establish the basis from which to set expectations for a specific soil to function. Evaluation of changes in soil quality is based on whether management has enhanced, sustained, or degraded the ability to provide the chosen service, without adverse effects on its surroundings. Soil provides the following basic functions or services:

- **Controlling water flow**. Soil helps control where rain, snowmelt, and irrigation water goes. Water and dissolved solutes flow either over the soil surface or into and through the soil profile.
- **Sustaining plant and animal productivity**. The diversity and productivity of living things depends on soil. This includes not only crops, but also soil biota such as earthworms and microbes that are beneficial for sustained crop production.
- **Filtering potential pollutants**. The minerals and microbes in soil are responsible for filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposits.
- **Cycling nutrients**. Carbon, nitrogen, phosphorus, and many other nutrients are stored, transformed, and cycled through the soil.
- **Supporting structures**. Soils provide a stable medium for plant root growth with sufficient porosity to allow solute flow and aeration. For land uses other than crop production, buildings need stable soil for support, and archeological treasures associated with human habitation are protected in soils.

The key to managing for improved soil quality for purposes of crop production is to manage for soil organic matter. Soil organic matter is the organic faction of the soil including plant and animal residues, soil organisms, and many combinations of chemical elements. Much of the soil organic matter consists of the element carbon. Carbon is key because we have the ability to manipulate it, and it has a major role in physical, chemical, and biological properties of soil.

Managing for carbon includes adding organic material such as manure and managing crop residues through reduced tillage, crop rotations, and cover crops. Through microbial breakdown of residues and other natural processes, soil carbon accumulates in the soil. The soil's structure improves through greater aggregation produced by water insoluble proteins and other organic products from the breakdown of residues that bind smaller particles together. This improved aggregation further resists the impacts of rainfall and enhances infiltration, providing more water for plant growth and less for runoff. The reduction in runoff improves water quality by reducing sediment and nutrient loads and increasing the use of the soil as a natural filter. Organic matter removes contaminants from the environment through strong chemical bonds with the soil, rendering the contaminants harmless, or degrading the contaminants to less toxic forms. A soil's ability to retain water is enhanced by the chemical nature of organic matter, which can hold from 10 to 1,000 times more water than inorganic soil matter.

Change in soil organic carbon is an indicator of soil quality. Cropland soils that are increasing in soil organic carbon over time will have an increased capacity to sustain plant and animal activity, retain and hold water, filter potential pollutants, and cycle nutrients—that is, enhanced soil function. However, not all cropland soils that are losing soil organic carbon are in a degraded state with respect to soil function. Loss of soil organic carbon is much less serious for cropland acres with inherently high levels of soil organic carbon than for acres with inherently low levels of soil organic carbon. Some soils with relatively high percent losses can continue to lose soil organic carbon for many years before soil function is impaired. Other soils, on the other hand, may only be able to tolerate very small percent losses before soil function is impaired.

A soil quality degradation indicator was developed to identify cropland acres where the potential for soil quality degradation is the greatest and, thus, where conservation practices to enhance soil quality would be needed the most. The soil quality degradation indicator was derived from a soil organic carbon indicator that adjusted soil organic carbon estimates to better reflect those cropland acres where soil organic carbon losses have a deleterious affect on soil function.

The soil organic carbon indicator

The soil organic carbon (SOC) indicator was calculated using the Soil Management Assessment Framework (SMAF), which was designed to assess the impact of soil management practices on soil function (Andrews et al. 2004; Andrews et al. 2002). While SMAF consists of three steps (indicator selection, interpretation, and integration into an index), only the integration step was used for development of the SOC indicator used in this report. The interpretation step was used to transform EPIC model estimates of SOC into unitless scores based on site-specific relationships between SOC and soil function. The indicator represents the ability of the soil to meet potential soil function to support crop production.

The SOC indicator scoring curve consists of an algorithm with parameters that change based on site-specific environmental factors. The basic curve shape was determined by literature review and consensus of collaborating researchers (Andrews et al. 2004). The scoring curve selected is an ascending logistic S-curve, or more-is-better function, based on the role of soil organic carbon in soil fertility, water partitioning, and structural stability (Tiessen et al. 1994; Herrick and Wander, 1998). A higher score (on a 0 to1 scale) represents greater performance of soil functions such as nutrient cycling and productivity.

Site-specific controlling factors (such as climate or inherent soil properties) are used to define the slope and inflection point of the scoring curve for specific soils. For instance, in a southeastern United States Ultisol, a SOC of 2 percent would be considered a high value because of the high decomposition rates that occur in that climate; this soil would receive a high SOC score. In a Midwestern Mollisol, however, a SOC of 2 percent would be considered a low value, consistent with a degraded soil, because these soils have inherently high SOC levels due to their formation under grasses and their cooler climates that yield lower decomposition rates. It would, therefore, receive a correspondingly low score. The factors controlling these differences

include average annual precipitation, average annual temperature, soil texture, and soil taxonomic suborder as a surrogate for inherent soil organic matter.

To model these associations between indicators, function, and controlling factors, one must have knowledge of (or make assumptions about) not only the appropriate curve shape (based on indicator performance of ecosystem function), but also the expected direction of change in curve inflections as major controlling factors change. For instance, as temperature and precipitation increase, expected SOC decreases because of increased decomposition rates. This results in a shift to the left in the inflection point of the scoring curve. For a given SOC value, a shift of the curve to the left produces a higher score compared with the same SOC value in a climate with inherently lower decomposition rates. The same is true for sandy soils versus clays; most sandy soils have inherently less organic matter than clays and the curve shifts to accommodate this phenomenon. Site-specific scoring enables the interpretation to reflect both overall soil function and inherent capabilities of the soil.

The SOC scoring curve used to calculate the SOC indicator is:

$$y = \frac{a}{\left(1 + b \times \exp^{-c \times soc}\right)}$$

The parameter "a" is set to 1.0 and the parameter "b" is set to 50.1 on the basis of empirical testing. The parameter "c" is a function of three factors: inherent organic matter, soil texture (Needelman et al. 1999), and climate (USDA 1966):

$$c = \left(iOM \times txt\right) + \left(iOM \times txt \times clim\right)$$

where:

iOM = a coefficient representing four classes of inherent organic matter grouped by soil suborder (USDA NRCS 1998; C. Seybold, personal communication)

txt = a coefficient for five soil texture levels defined by Quiesenberry et al. (1993)

clim = a coefficient derived from average annual precipitation and degree days above freezing (USDA SCS 1981; Bailey 1995) for major land resource areas

For the inherent organic matter factor, soil suborders were grouped into four classes based on their inherent levels of soil organic matter according to the following table. The "iOM" coefficients are also listed.

Class	Suborder	Coefficient
1	Aquands, Aquods, Aquox, Fibrists, Folists, Hemists, Histels, Saprists, Turbels	0.3
2	Albolls, Aquepts, Aquerts, Aquolls, Aquults, Borolls, Cryolls Muhods, Humolts, Rendolls, Udands, Udolls, Udox, Ustands, Ustolls, Xerests, Xerolls	1.55
3	Andepts, Anthrepts, Aqualfs, Aquents, Boralfs, Cryalfs, Cryands, Cryerts, Cryods, Orthels, Udalfs, Ustalfs, Vitrands, Xeralfs	2.17
4	Arents, Argids, Calcids, Cambids, Cryepts, Cryids, Durids, Fluvents, Gypsids, Ochrepts, Orthents, Orthids, Orthods, Orthox, Perox, Psamments, Salids, Torrands, Torrerts, Torrox, Tropepts, Udepts, Udults, Umbrepts, Ustepts, Ustox, Ustults, Xerands, Xerepts, Xerents, Xerults	3.81

The five soil texture classes used for the texture factor were based on water movement as related to soil particle size. The five classes and coefficients are:

Class	Textures	Coefficient
1	sand, loamy sand, or sandy loam (with <8% clay)	1.6
2	Sandy loam (≥ 8% clay), sandy clay loam, or loam	1.25
3	silt loam, silt	1.1
4	Sandy clay, clay loam, silty clay loam, silty clay or clay (<60% clay)	1.05
5	clay (>60% clay)	1

The four climate classes used for the climate factor were based on average annual degree days above freezing and average annual precipitation. The four classes and coefficients are:

Class	Average annual degree days	Average annual precipitation	Coefficient
1	≥ 170 °days	≥ 550 mm	0.15
2	≥ 170 °days	< 550 mm	0.05
3	< 170 °days	≥ 550 mm	-0.05
4	< 170 °days	< 550 mm	-0.01

The SOC indicator score was calculated for each cropland sample point included in the study for model output for years 1 and 30. Because the above SOC scoring curve is calibrated for percent SOC by weight, the EPIC model estimate of soil organic carbon in units of tons per acre had to be converted. The formula for conversion uses both soil bulk density and sample depth. The initial bulk density value was used for each representative soil cluster and assumed a uniform soil depth of 30 centimeters (11.8 in) for this conversion. The controlling factor information was obtained from the model input parameters for soil and climate.

An SOC indicator score ranging between zero and one was then determined for each modeled NRI point using the scoring curve (above). A SOC indicator score was determined for both the first year in the model simulation output (year 1) and the last year (year 30).

The soil organic carbon indicator score for the last year of the model simulation is shown in map 39. As described previously, the distance-weighted average value over several NRI cropland points is represented in each 25 square kilometer (9.6 mi^2) grid cell on the map. High scores are indicative of soil organic carbon levels that provide nearly full soil function for purposes of crop production, such as nutrient cycling and water partitioning. Similarly, low scores indicate that soils are very low in carbon relative to inherent levels, and thus soil function could be improved with appropriate management. Comparing map 39 to map 35 (average per-acre soil organic carbon) provides an example of what the soil organic carbon indicator represents. Acres with very high soil organic carbon levels tended to score high, and acres with very low soil organic carbon levels tended to score low. In several regions, however, acres with modest levels of soil organic carbon also scored high. About 77 percent of the acres had SOC scores greater than 0.90, indicating they were meeting or nearly meeting the full potential of the soil to support crop production at the end of the 30-year simulation.

The soil quality degradation indicator

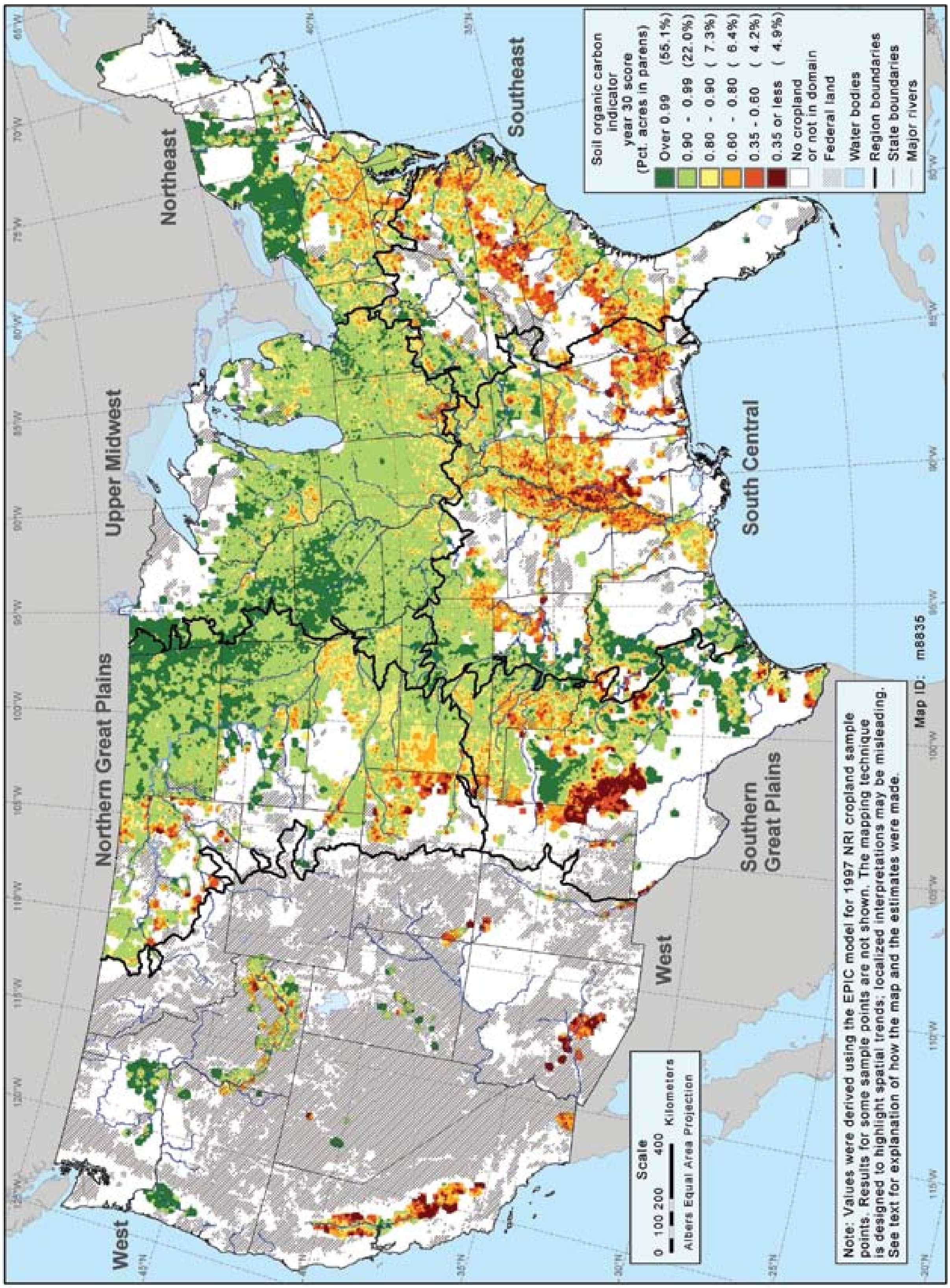
Whereas the soil organic carbon indicator is a better representation of soil function than the level of soil organic carbon, the score for any given year does not indicate whether the soil function capability is improving or worsening, which is important in identifying cropland areas where soil quality is degrading.

The soil quality degradation indicator was determined on the basis of the 30-year change in the soil organic carbon indicator and the indicator score for the last year of the simulation. The 30-year change in the soil organic carbon indicator was calculated as the difference between the SOC indicator score for the first year and the SOC indicator score for the last year in the 30-year simulation. Results showed that 73.6 percent of the acres had a negative change in SOC score between year 1 and year 30, indicating that soil condition was decreasing over the 30-year simulation period. For sample points with a positive change, the soil quality degradation indicator was set equal to the SOC score for year 30. For sample points with a negative change, the soil quality degradation indicator was set equal to one minus the SOC score for year 30 and converted to a negative number. Subtracting the SOC score from one is necessary to preserve the ranking of the original score.

Thus, the soil quality degradation indicator is a modification of the SOC indicator score for year 30, adjusted to reflect whether or not the score is increasing or decreasing at a point and adjusted to preserve the ranking that the SOC indicator score provides. The soil quality degradation indicator for sample points with increasing SOC indicator scores ranged from 0 to 1. The soil quality degradation score for sample points that were decreasing ranged from -1 to 0, with 0 corresponding to the SOC indicator score of 1. The resulting distribution for the soil quality degradation indicator scores is:

Soil quality degradation indicator score	Percent acres
>0.90	19.3
0.60 to 0.90	4.1
0.25 to 0.60	1.8
>0.0 to 0.25	1.2
0 to -0.01	41.4
-0.12 to -0.01	17.8
-0.35 to -0.12	7.7
<-0.35	6.8
Total	**100.0**

Map 39 Soil organic carbon indicator (year 30 score)



Cropland acres with increasing SOC indicator scores comprised 26.4 percent of the acres. The bulk of these acres scored above 0.90, representing nearly fully functioning or fully functioning soils that were improving over time. About 41.4 percent of the acres had a score of zero or nearly zero. These acres all had negative values for the change in the SOC indicator, but still had SOC indicator scores close to one in year 30 of the simulation. Even though the SOC score was declining for these acres, it was declining so slowly that soil quality degradation would probably not be a concern.

Acres that are at most risk of soil quality degradation—and thus loss of soil function—comprise the remaining third of the acres. These acres would benefit the most from conservation practices designed to enhance soil quality. The spatial distribution of the soil quality degradation indicator scores is shown in map 40. The most vulnerable acres from a soil quality standpoint are the areas colored orange, red, and brown. The brown areas, which indicate areas where the average soil quality degradation indicator score is below -0.35, are the most sensitive cropland acres. About 7 percent of the acres included in the study have scores in this range. These sensitive acres are most concentrated in the southern half of the United States. The orange and red areas, representing average soil quality degradation indicator scores ranging from just below zero to -0.35, are often adjacent to the most sensitive acres, but can also be found scattered throughout most cropland areas.

Note that the mapping process calculates the average score for sample points within each grid cell and assigns a color to the grid cell based on that average score. The map thus depicts the general spatial trends showing where the most vulnerable soils tend to be concentrated. The visual representation of acres in the classes shown in map 40, however, will not always correspond to the distribution statistics obtained from the NNLSC database and reported in the table above.

Reflecting the spatial trends shown in map 40, the distribution of soil quality degradation indicator scores varies markedly from region to region, as shown in table 69. The average soil quality degradation indicator score was negative for only one region—the Southern Great Plains region (-0.119). In this region, 75 percent of the acres had a soil quality degradation indicator score less than zero. The Southeast and South Central regions had the next lowest average soil quality indicator scores, where more than 50 percent of the acres had negative scores. The highest average scores were for the Northeast region (0.332) and the Upper Midwest region (0.278). All regions, however, had significant acreage with negative soil quality degradation indicator scores.

Assessment of critical acres for soil quality degradation

Acres with the lowest negative soil quality degradation indicator scores are identified here as critical acres. Following the same approach used to identify critical acres for soil and nutrient loss, five categories of critical acres, representing different degrees of severity, are defined on the basis of national level results:

- acres where the soil quality degradation indicator is below the 5th percentile (-0.488) for all acres included in the study
- acres where the soil quality degradation indicator is below the 10th percentile (-0.220) for all acres included in the study
- acres where the soil quality degradation indicator is below the 15th percentile (-0.113) for all acres included in the study
- acres where the soil quality degradation indicator is below the 20th percentile (-.0.060) for all acres included in the study
- acres where the soil quality degradation indicator is below the 25th percentile (-0.025) for all acres included in the study

Critical acres for soil quality degradation are less concentrated in one or two regions than was the case for sediment loss, wind erosion, or nutrient loss. About 65 percent of the critical acres in the bottom 5 percent category were in the South Central region (33.4% of critical acres) and the Southern Great Plains region (31.6%) (table 70). All regions had critical acres in this category. As the criterion for critical acres expanded from the bottom 5 percent category to the bottom 25 percent category, the representation of critical acres in other regions expanded to a more balanced distribution of critical acres among four of the regions, with significant representation in all but the West region.

Map 40 Soil quality degradation indicator for cropland

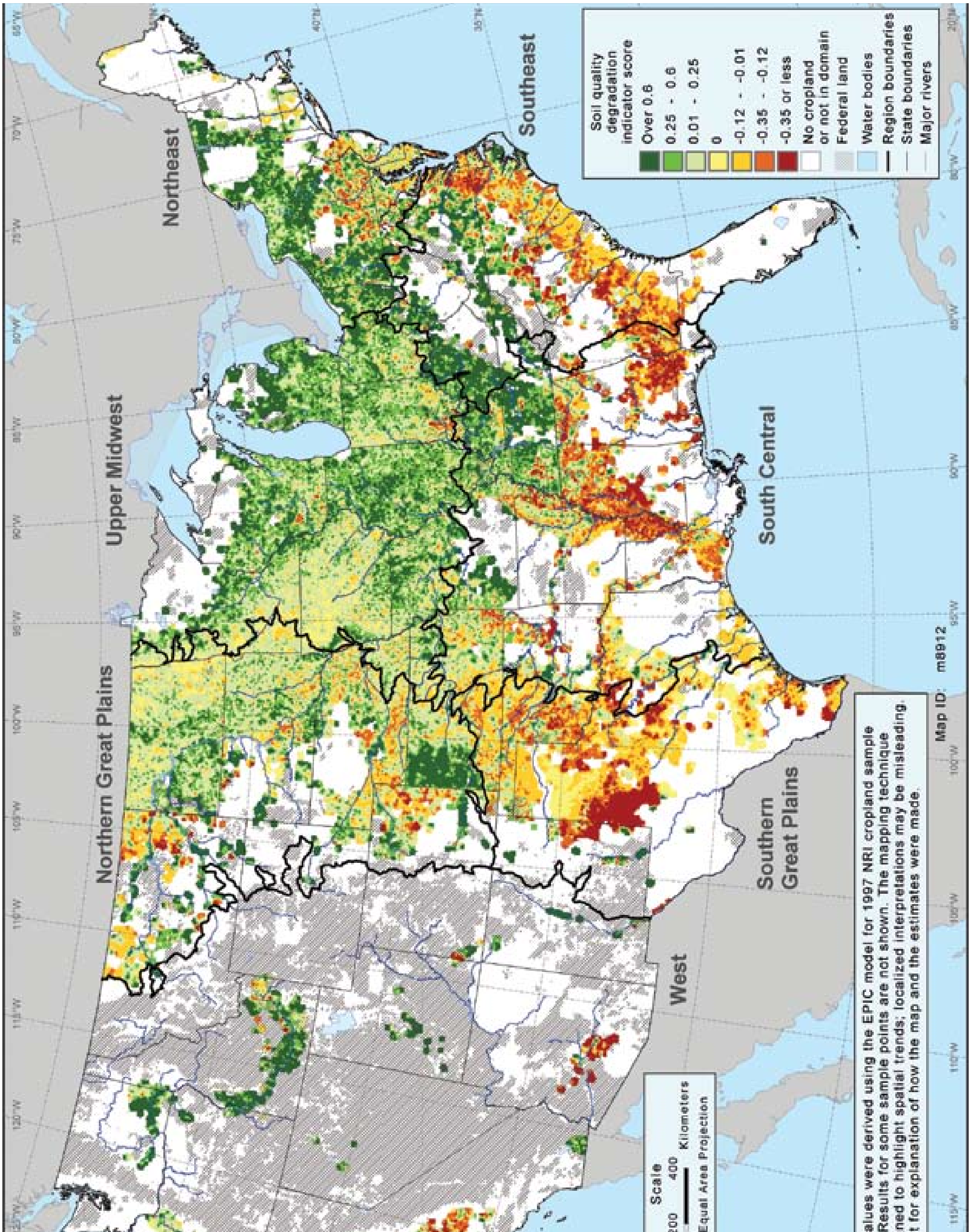


Table 69 Percentiles for the soil quality degradation indicator

Region	Acres	Number of NRI sample points	Mean	5th percentile	10th percentile	25th percentile	50th percentile	75th percentile	90th percentile	95th percentile
Northeast	13,641,900	11,282	0.332	-0.449	-0.290	-0.079	0.000	1.000	1.000	1.000
Northern Great Plains	72,396,500	36,035	0.154	-0.219	-0.099	-0.010	0.000	0.000	0.994	1.000
South Central	45,349,900	27,465	0.047	-0.710	-0.532	-0.159	-0.009	0.000	0.961	1.000
Southeast	13,394,400	8,955	0.100	-0.719	-0.490	-0.160	-0.006	0.412	1.000	1.000
Southern Great Plains	32,096,000	14,495	-0.119	-0.880	-0.710	-0.170	-0.010	0.000	0.000	0.301
Upper Midwest	112,580,900	74,691	0.278	-0.128	-0.060	-0.003	0.000	0.948	1.000	1.000
West	9,018,400	5,644	0.241	-0.818	-0.665	-0.074	0.036	0.972	1.000	1.000
All regions	298,478,000	178,567	0.164	-0.488	-0.220	-0.025	0.000	0.300	0.999	1.000

Note: Percentiles are in terms of acres. The 5th percentile, for example, is the threshold below which 5 percent of the acres have lower soil quality degradation indicator scores.

Table 70 Critical acres for the soil quality degradation indicator

		Soil quality indicator score in bottom 5% nationally		Soil quality indicator score in bottom 10% nationally		Soil quality indicator score in bottom 15% nationally		Soil quality indicator score in bottom 20% nationally		Soil quality indicator score in bottom 25% nationally	
Region	**Acres**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**	**Acres**	**Percent**
Northeast	13,641,900	594,200	4.0	1,829,100	6.2	2,866,100	6.4	3,775,100	6.3	4,524,800	6.1
Northern Great Plains	72,396,500	1,559,500	10.5	3,576,700	12.0	6,952,200	15.5	9,911,100	16.5	12,830,900	17.2
South Central	45,349,900	4,982,800	33.4	9,104,400	30.7	12,745,000	28.5	15,705,700	26.1	19,213,500	25.8
Southeast	13,394,400	1,355,600	9.1	2,946,100	9.9	4,279,000	9.6	5,191,100	8.6	5,810,600	7.8
Southern Great Plains	32,096,000	4,717,100	31.6	7,661,200	25.8	8,930,900	20.0	11,494,700	19.1	14,325,500	19.2
Upper Midwest	112,580,900	498,000	3.3	2,807,300	9.5	6,955,100	15.5	11,738,200	19.5	15,392,900	20.6
West	9,018,400	1,215,300	8.1	1,763,400	5.9	2,034,200	4.5	2,292,400	3.8	2,508,500	3.4
All regions	298,478,000	14,922,500	100.0	29,688,200	100.0	44,762,500	100.0	60,108,300	100.0	74,606,700	100.0

Note: The bottom 5 percent corresponds to the 5th percentile in table 69. Other columns correspond to table 69 in a similar manner.

Priority cropland acres with the highest potential for soil loss, nutrient loss, and soil quality degradation

The purpose of this study is to identify cropland areas of the country that have the highest potential for soil loss and nutrient loss from farm fields, as well as the highest potential for soil quality degradation—areas of the country that would likely benefit the most from conservation practices. Eight onsite (field level) environmental outcomes were used to identify critical cropland acres:

- sediment loss from water erosion (ton/a/yr, not including gully erosion)
- wind erosion rate (ton/a/yr)
- nitrogen lost with waterborne sediment (lb/a/yr)
- nitrogen dissolved in surface water runoff (lb/a/yr)
- nitrogen dissolved in leachate (lb/a/yr)
- phosphorus lost with waterborne sediment (lb/a/yr)
- phosphorus dissolved in surface water runoff (lb/a/yr)
- soil quality degradation indicator

Previous sections discuss cropland areas that are potentially the most vulnerable for each of the eight onsite environmental outcomes and define critical acres for each outcome for five categories representing different degrees of severity.

Priority acres are those designated as critical acres for one or more of the eight onsite environmental outcomes. Five categories of priority acres, each representing different thresholds of severity, are defined following directly from the approach used to identify critical acres for each outcome:

- most critical 5-percent category—consists of critical acres for sediment and nutrient loss estimates in the top 5 percent nationally (95th percentile), wind erosion rates in the top 2 percent nationally (98th percentile), and soil quality degradation indicator scores in the bottom 5 percent nationally (5th percentile)
- most critical 10-percent category—consists of critical acres for sediment and nutrient loss estimates in the top 10 percent nationally (90th percentile), wind erosion rates in the top 4 percent nationally (96th percentile), and soil quality degradation indicator scores in the bottom 10 percent nationally (10th percentile)
- most critical 15-percent category—consists of critical acres for sediment and nutrient loss estimates in the top 15 percent nationally (85th percentile), wind erosion rates in the top 6 percent nationally (94th percentile), and soil quality degradation indicator scores in the bottom 15 percent nationally (15th percentile)
- most critical 20-percent category—consists of critical acres for sediment and nutrient loss estimates in the top 20 percent nationally (80th percentile), wind erosion rates in the top 8 percent nationally (92nd percentile), and soil quality degradation indicator scores in the bottom 20 percent nationally (20th percentile)
- most critical 25-percent category—consists of critical acres for sediment and nutrient loss estimates in the top 25 percent nationally (75th percentile), wind erosion rates in the top 10 percent nationally (90th percentile), and soil quality degradation indicator scores in the bottom 25 percent nationally (25th percentile)

The most critical 5-percent category accounted for about 23 percent of the cropland acres included in the study (table 71). Thus, according to these model simulations, one or more of the eight onsite environmental outcomes was in the worst 5 percentile nationally (2 percentile for wind erosion) for 23 percent of the cropland acres. For perspective, note that if all of these acres met the critical acre criterion exclusively for only one environmental outcome, the top 5-percent category would represent 37 percent of the cropland acres—seven outcome categories times 5 percent of the acres for each plus 2 percent for wind erosion. The most critical 10-percent category included about 40 percent of the acres included in the study, the most critical 15-percent category included 52 percent of the acres, the most critical 20-percent category included 62 percent of the acres, and the most critical 25-percent category included 71 percent of the acres.

Table 71 Priority cropland acres with the highest potential for sediment loss, wind erosion, nutrient loss, or soil quality degradation

	Non-critical acres (1,000s)	Number of onsite environmental outcome categories meeting criteria for critical acres							Total critical acres (1,000s)	Percent critical acres
		1 (1,000 acres)	2 (1,000 acres)	3 (1,000 acres)	4 (1,000 acres)	5 (1,000 acres)	6 (1,000 acres)	7* (1,000 acres)		
Most critical 5% category										
Northeast	7,673	2,774	902	1,184	782	311	17	0	5,969	43.8
Northern Great Plains	69,703	2,177	483	32	0	0	2	0	2,694	3.7
South Central	25,404	12,315	4,605	1,522	1,021	417	56	11	19,946	44.0
Southeast	6,635	4,905	1,072	348	385	35	12	3	6,760	50.5
Southern Great Plains	24,294	4,849	2,922	31	0	0	0	0	7,802	24.3
Upper Midwest	93,021	10,124	4,783	3,858	716	55	23	0	19,560	17.4
West	4,151	3,519	1,254	78	1	17	0	0	4,868	54.0
All regions	230,880	40,662	16,021	7,053	2,906	834	109	14	67,598	22.6
Most critical 10% category										
Northeast	4,861	4,091	955	974	1,661	857	201	42	8,781	64.4
Northern Great Plains	65,316	5,409	1,275	333	61	2	2	0	7,081	9.8
South Central	14,580	14,188	7,351	4,644	2,150	1,703	692	42	30,770	67.8
Southeast	3,720	5,785	2,217	739	623	159	143	9	9,675	72.2
Southern Great Plains	18,223	8,187	5,460	217	10	0	0	0	13,873	43.2
Upper Midwest	69,683	22,767	7,756	8,145	3,109	856	259	6	42,898	38.1
West	3,474	3,270	1,950	288	9	15	13	0	5,545	61.5
All regions	179,856	63,696	26,964	15,340	7,623	3,591	1,309	99	118,622	39.7
Most critical 15% category										
Northeast	3,266	4,100	1,714	793	1,496	1,519	577	178	10,376	76.1
Northern Great Plains	58,346	9,240	2,908	1,123	666	112	0	2	14,051	19.4
South Central	10,901	10,115	8,309	6,684	3,998	3,156	1,833	355	34,449	76.0
Southeast	2,233	4,853	3,667	1,183	725	427	256	51	11,162	83.3
Southern Great Plains	15,437	7,984	7,832	786	51	5	0	0	16,659	51.9
Upper Midwest	49,903	28,808	12,962	11,195	6,673	2,207	753	79	62,678	55.7
West	3,222	3,108	2,036	560	59	10	24	0	5,797	64.3
All regions	143,307	68,208	39,427	22,324	13,668	7,436	3,443	664	155,171	52.0
Most critical 20% category										
Northeast	1,517	4,882	1,724	890	1,191	1,804	1,236	399	12,125	88.9
Northern Great Plains	51,511	11,848	5,219	2,063	1,140	610	4	2	20,886	28.8
South Central	7,835	7,993	6,776	7,140	5,921	4,191	4,510	984	37,515	82.7
Southeast	1,521	4,018	3,779	1,829	1,105	559	462	123	11,874	88.6
Southern Great Plains	12,198	8,867	8,486	2,367	161	18	0	0	19,898	62.0
Upper Midwest	36,835	30,675	14,263	14,699	9,470	4,280	1,605	754	75,746	67.3
West	2,888	2,991	2,301	724	44	48	24	0	6,131	68.0
All regions	114,304	71,273	42,547	29,710	19,031	11,509	7,841	2,262	184,174	61.7

Table 71 Priority cropland acres with the highest potential for sediment loss, wind erosion, nutrient loss, or soil quality degradation—Continued

	Non-critical acres (1,000s)	Number of onsite environmental outcome categories meeting criteria for critical acres							Total critical acres (1,000s)	Percent critical acres
		1 (1,000 acres)	2 (1,000 acres)	3 (1,000 acres)	4 (1,000 acres)	5 (1,000 acres)	6 (1,000 acres)	7* (1,000 acres)		
Most critical 25% category										
Northeast	584	5,043	1,862	815	1,011	1,985	1,611	732	13,058	95.7
Northern Great Plains	44,007	16,273	5,227	3,827	2,004	983	74	2	28,390	39.2
South Central	5,484	5,964	6,684	6,519	6,060	6,049	6,053	2,537	39,866	87.9
Southeast	1,227	3,430	3,622	1,790	1,508	860	697	261	12,168	90.8
Southern Great Plains	10,124	8,712	9,190	3,491	490	84	5	0	21,972	68.5
Upper Midwest	24,220	31,277	14,673	18,098	13,413	6,745	2,669	1,486	88,361	78.5
West	2,422	2,925	2,476	775	310	63	48	0	6,597	73.1
All regions	88,067	73,624	43,734	35,314	24,796	16,769	11,156	5,018	210,411	70.5

Note: The most critical 5 percent category includes critical acres for sediment and nutrient loss estimates in the top 5 percent nationally, wind erosion rates in the top 2 percent nationally, and soil quality degradation indicator scores in the bottom 5 percent nationally. The higher percent categories were constructed in an analogous manner, using the top 4-, 6-, 8-, and 10-percent wind erosion rates.
* Includes less than 10,000 acres with eight onsite environmental outcomes for the most critical 25 percent category

Cropland acres were often critical for more than one onsite environmental outcome, also shown in table 71. Of the 68 million cropland acres meeting criteria for critical acres in the most critical 5-percent category, 40 percent met criteria for more than one outcome. Most of these met criteria for just two outcomes, but a significant number met criteria for three or four outcomes. Multiple outcomes were less prevalent in the Northern Great Plains, Southern Great Plains, and West regions. As the criteria for critical acres expanded to include less severe outcomes, critical acres meeting criteria for multiple outcomes increased. About 56 percent of the priority acres met criteria for more than one outcome in the most critical 15-percent category and 65 percent met criteria for more than one outcome in the most critical 25-percent category. These cropland acres that are critical for multiple onsite environmental outcomes are potentially in the greatest need of conservation treatment, and, if treated, would provide the most overall environmental protection for the least effort.

The spatial distribution of priority acres is shown in maps 41–44 for the most critical 5-percent, most critical 10-percent, most critical 15-percent, and most critical 20-percent categories. The color scheme in these maps reflects the number of onsite environmental outcomes that met the criteria for critical acres. A blue cell in the maps, for example, has an average cell value for one of the eight onsite environmental outcomes that meets the criteria for critical acres on the basis of the NRI acreage represented by the 25-square-mile cells used to construct the maps. Green represents critical acres for two onsite environmental outcomes, orange represents critical acres for three or four outcomes, and red represents acres for five or more outcomes that met criteria for critical acres. For perspective, map 45 shows the areas of the country with the greatest concentration of cropland acres.

For maps 41–44, thresholds were based on the average values for the 25-mi^2 cells, rather than on the estimates for individual NRI sample points. For the most critical 5% category (map 41), for example, cells were colored if the average cell value for sediment loss or one of the five nutrient loss outcomes was in the 5% of cropland acres with the highest values, or if the average cell value for wind erosion was in the top 2% of the acres, or if the average cell value of the soil quality degradation indicator was in the bottom 5% of the acres.

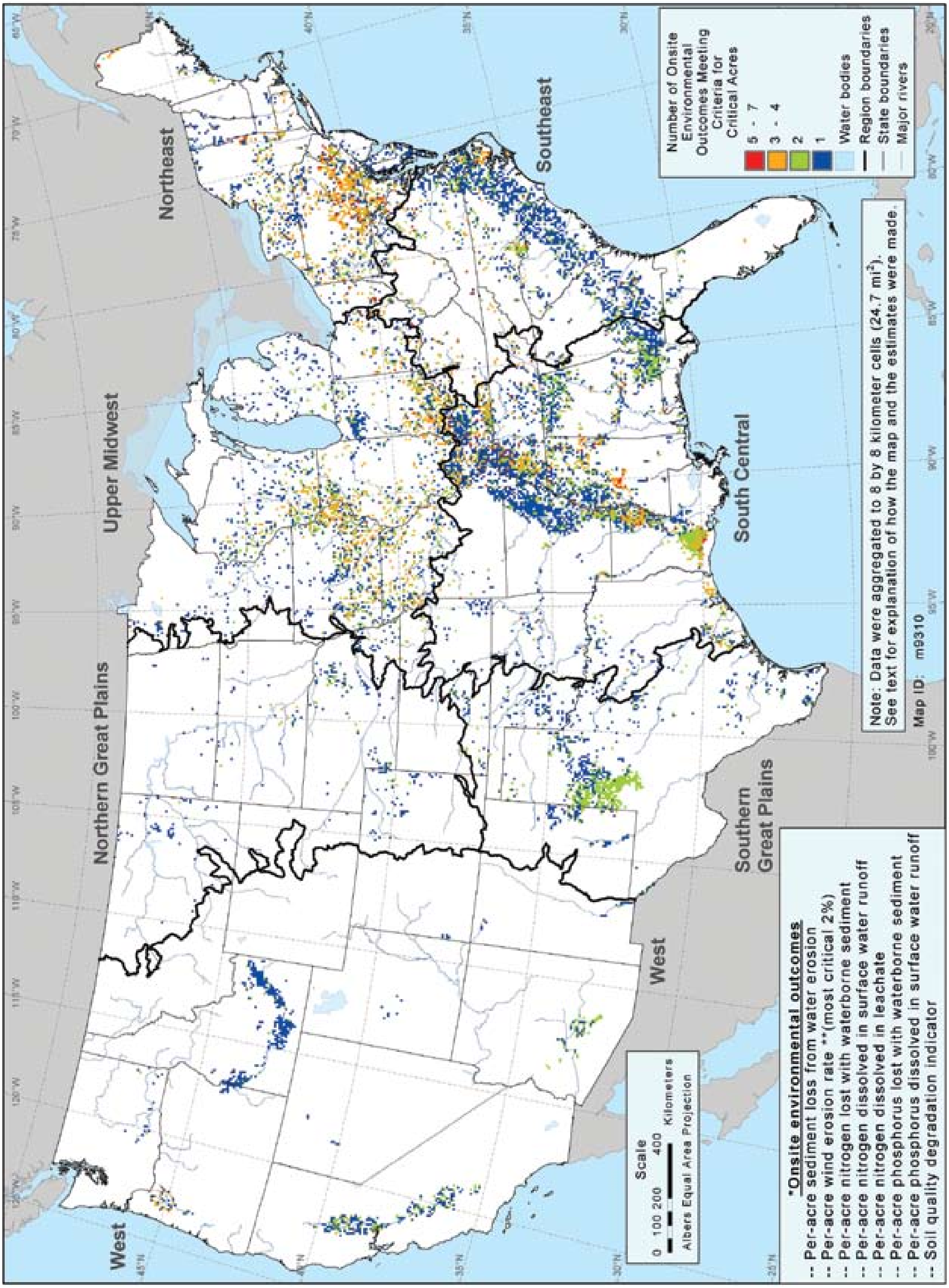
The 68 million potential priority acres shown in map 41 for the most critical 5-percent category are generally distributed throughout most of the cropland areas, as can be seen by comparing map 41 to map 45. However, the priority acres are most concentrated in six areas:

- cropland in the Chesapeake Bay watershed in Maryland and Pennsylvania—area includes the largest concentration of critical acres for multiple outcomes, most of which are critical for three or more outcomes and sometimes five or more
- cropland in the Lower Mississippi River Basin on either side of the Mississippi River below St. Louis, including the lower reaches of the Ohio River, which included several pockets of concentrations of critical acres for multiple outcomes
- cropland along the Atlantic coastal plain stretching from Alabama to southern Virginia
- cropland in northern Texas and western Oklahoma, including a concentration of critical acres in western Texas that met criteria for two outcomes
- cropland in the southern two-thirds of Iowa and parts of Illinois and Missouri adjacent to Iowa, with a significant portion of the critical acres meeting criteria for up to four outcomes
- selected cropland areas in the West

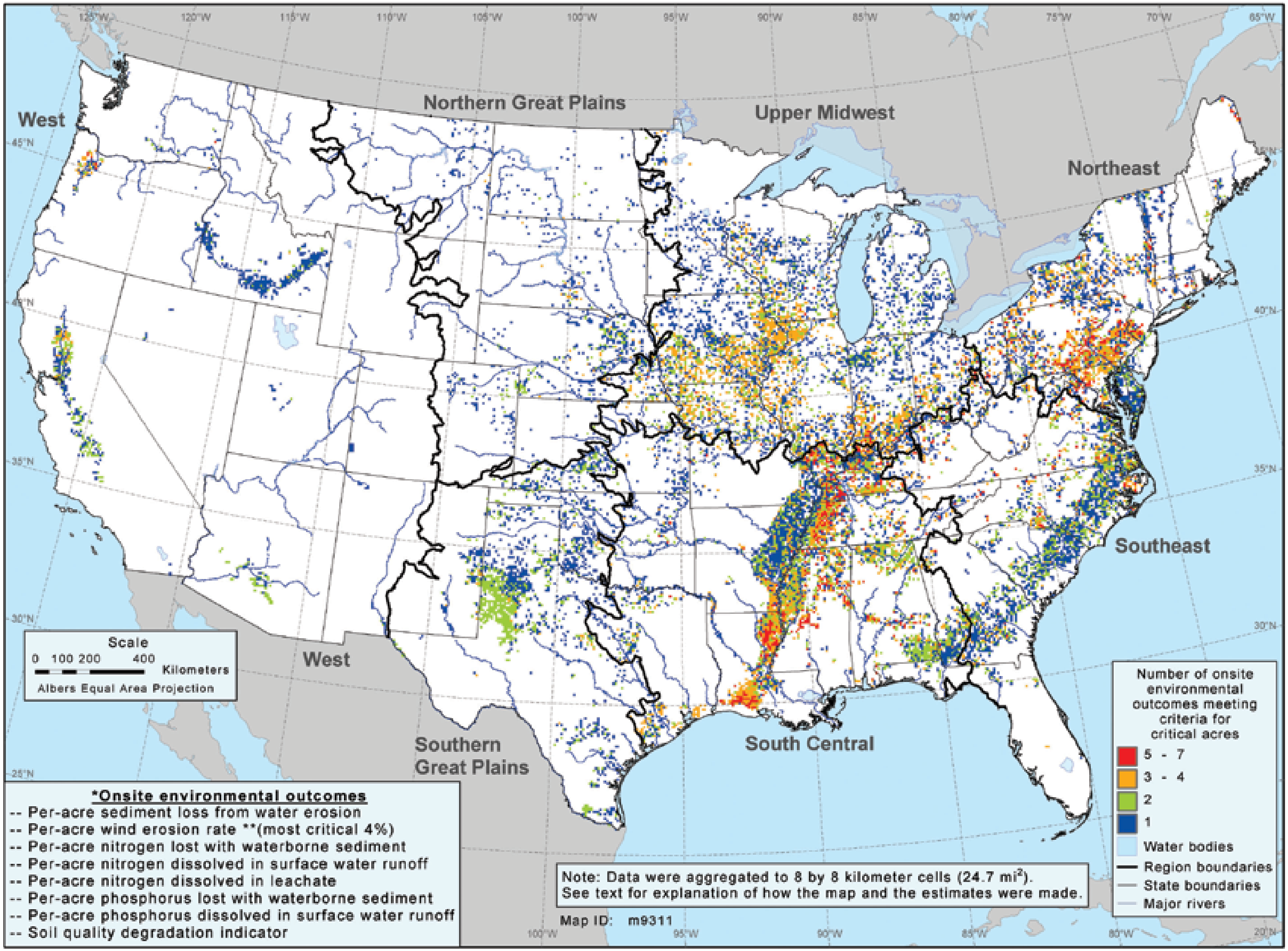
Much of the concentrated cropland area in the Midwest stretching from Ohio through Iowa and eastern Nebraska did not have heavy concentrations of potential priority acres at this level of severity. With the exception of the Lower Mississippi River Basin area, most potential priority acres are found in cropland regions where cropland represents less than 60 percent of the land use.

Relaxing the thresholds for critical acres from the most critical 5-percent category to the most critical 10-percent category increased the number of potential priority acres by 75 percent—from 68 million acres to 119 million acres (map 42). The additional priority acres reinforced the concentration in the six areas identified above, and expanded the number of priority acres in the Midwest region by 23 million acres—more than double the number of priority acres for the 5-percentile category. Priority acres more than doubled in the Northern Great Plains region, as well, although,

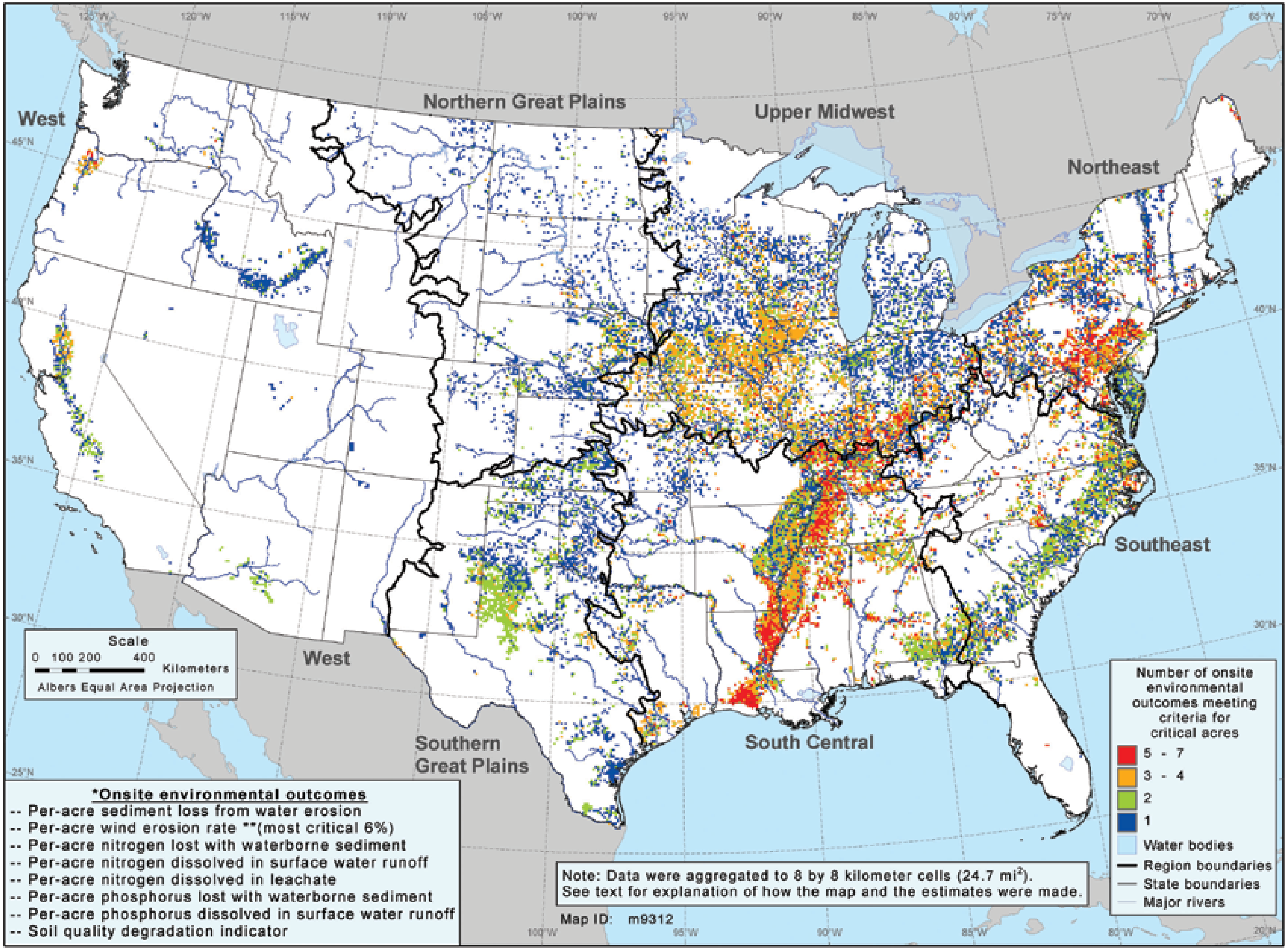
Map 41 Number of onsite environmental outcomes* with most critical 5 percent** of cropland acres for each outcome (most critical 5% category)



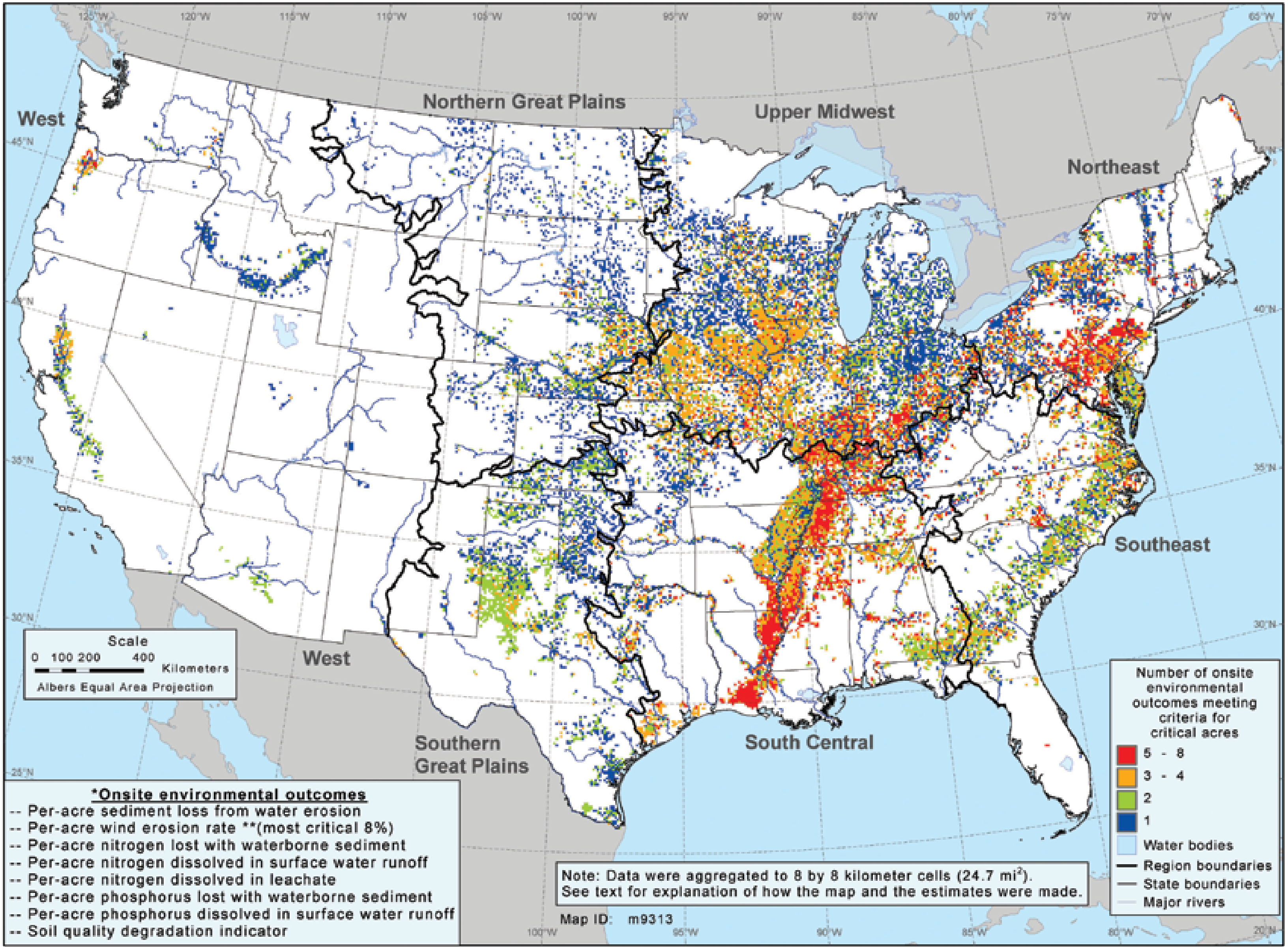
Map 42 Number of onsite environmental outcomes* with most critical 10 percent** of cropland acres for each outcome (most critical 10% category)



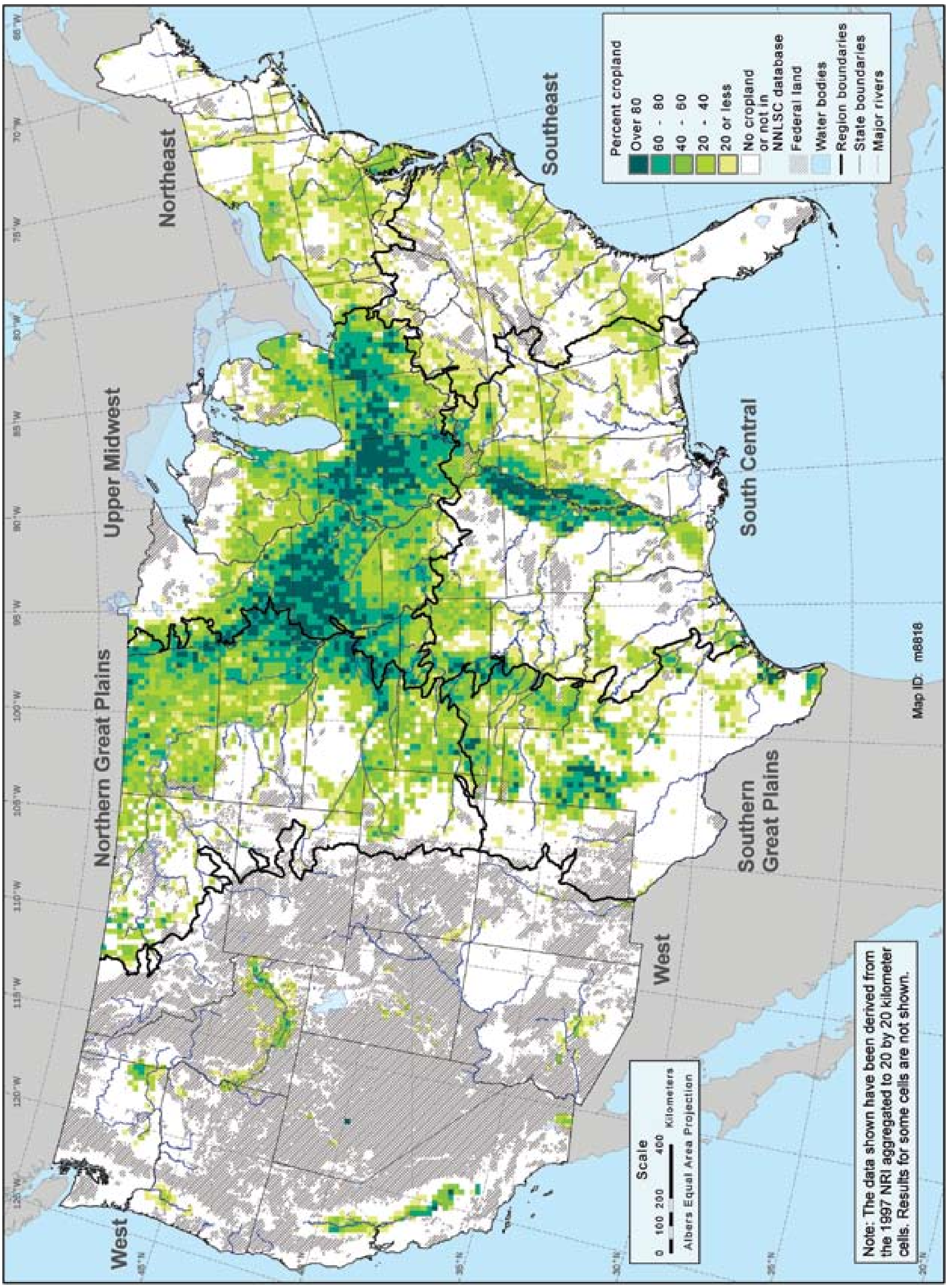
Map 43 Number of onsite environmental outcomes* with most critical 15 percent** of cropland acres for each outcome (most critical 15% category)



Map 44 Number of onsite environmental outcomes* with most critical 20 percent** of cropland acres for each outcome (most critical 20% category)



Map 45 Cropland acres included in the study as a percent of all land uses



they tended to be somewhat evenly spread throughout the cropland acres in the region. The number of priority acres that were critical for multiple onsite environmental outcomes also increased. Acres with three or more outcomes with critical acres (colored orange) more than tripled, and those with five or more (colored red) expanded by more than five times. At the top 10-percent level of severity, two cropland areas had heavy concentrations of priority acres critical for five or more outcomes—the Lower Mississippi River Basin area and the Pennsylvania-Maryland area north of the Chesapeake Bay.

At the severity level of the most critical 15-percent category, about half of the cropland acres were critical acres for one or more onsite environmental outcomes (map 43). The Iowa-Illinois-Missouri area of concentration is more pronounced at this level of severity; most priority acres in this area were critical for three to four outcomes. Most of the priority acres along the Atlantic Coastal Plain are critical for two outcomes, whereas most were critical for only one outcome in the most critical 5-percent category. About 36 million acres were critical for three to four outcomes at this level of severity, and about 12 million acres were critical for five or more outcomes. Nearly all cropland areas had at least some critical acres, but concentrations of critical acres and concentrations of critical acres with multiple outcomes were not always in areas with the highest percentage of cropland. For example, the eastern edge of the Northern Great Plains region is predominately cropland (map 45), but, while it has priority acres scattered throughout most of this area, does not have any areas of concentrated critical acres. The same applies to northern Iowa and southwestern Minnesota, where more than 80 percent of the acres are cropland in some parts.

Expanding the set of priority acres to the most critical 20-percent category (map 44) reinforced the patterns and spatial trends shown in map 43. The Lower Mississippi River Basin and the Pennsylvania-Maryland areas were almost entirely represented by critical acres for five or more outcomes, and the Iowa-Illinois-Missouri area of concentration was largely represented by critical acres for three or four outcomes. Overall, 50 million acres (a sixth of the acres included in the study) were critical for three to four outcomes at this level of severity, and 21 million acres were critical for five or more outcomes. The heaviest concentrations of the highest priority acres—those critical for five or more outcomes—were the Lower Mississippi River Basin and adjacent areas along the lower Ohio River drainage and the Pennsylvania-Maryland region north of the Chesapeake Bay.

An assessment of priority cropland acres, as determined by the per-acre model simulation results presented in this report, leads to the following conclusions:

- Critical cropland acres that are most in need of conservation treatment to manage soil loss, nutrient loss, or soil quality degradation are distributed throughout all the major cropland areas of the country.
- Critical acres are more concentrated in some regions of the country than in other regions.
- The loss pathways and specific treatment needs vary from region to region; for example, the most critical acres for nitrogen runoff loss and nitrogen leaching loss are primarily in different cropland areas.
- Some cropland areas have high concentrations of critical acres for multiple onsite environmental outcomes. These acres represent the highest priority acres for conservation treatment.

Critical acres are identified in this study based only on per-acre losses or soil quality conditions, representing those cropland acres where investment in conservation practices would potentially have the greatest benefits at the field level. Most conservation practices are designed to abate pollution sources at the field level. However, there are other considerations that can also factor into the determination of priority areas for conservation program implementation:

- For some environmental issues, the concern is primarily related to the total amount of sediment or nutrients leaving farm fields and being transported to other areas, impairing water quality in downstream ecosystems. To address these concerns, the areas with the most total loadings would be the highest priority.
- The potential for mitigating impairment of water quality in downstream ecosystems by treating the land is dependent on the potential for the sediment and nutrient losses to be transported from the edge of the field (or through ground water return flow) to a stream or river. It is further

dependent on the existing condition of the water resource, designated uses, and other pollution sources. An evaluation of how effective land treatment would be in ameliorating water quality impairment could lead to identification of a different set of priority acres in some cases.

- Acres that are the most degraded may be the most difficult and expensive to treat. It is possible that treatment of only a few acres with high severity does not provide as much environmental protection as the treatment of more acres that are less severe but easier and cheaper to treat.
- Critical acres in this study were identified on the basis of the annual average amount of nutrients or soil lost from farm fields, averaging over model results for 30 years of different weather conditions. This annual average represents what would be expected under typical weather conditions. For some years in the simulation, however, much higher losses occurred. A somewhat different picture of potential problem areas might be obtained if it was based on the worst case, or near-worst case, outcomes, rather than the average outcome.

Because only tillage and three structural practices were considered in this study, results are presented as potential losses of soil and nutrients from farm fields and the potential for soil quality degradation. Accounting for conservation practices such as nutrient management plans, cover crops, grassed waterways, windbreaks, and buffers, for example, is expected to further reduce sediment and nutrient loss estimates. Moreover, limitations such as incomplete cropland coverage (especially in the West) and the lack of site-specific management practices including crop rotations, as well as various modeling limitations noted previously, are additional reasons to consider the model output as potential losses of soil and nutrients. The priority acres identified are, thus, also potential priority areas. Efforts are currently underway in CEAP to improve the modeling routines, obtain more complete site-specific information, and fully account for conservation practices. Model outputs presented in forthcoming CEAP reports are expected to differ somewhat from results reported in this study and may have some impact on the designation of priority acres.

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Appendix A Example calculation of weighted average EPIC model outputs assigned to NRI sample points

As described in the main body of the report, the NNLSC database consists of EPIC model results for 768,785 model runs providing, on average, about 30 different simulations for each of 25,250 URUs. The results of the EPIC model runs were used to construct model-generated variables for the 178,567 NRI cropland points included in the domain. Variable values for an NRI sample point were obtained by calculating the weighted average over all the management options in the NNLSC database for the URU corresponding to the NRI sample point. Each NRI sample point corresponding to a given URU was assigned the same variable values. The weights represent the probability that a particular option would occur.

The probabilities that a particular management option applies to a URU (and the associated NRI sample points) were estimated based on the frequency of occurrence of each option obtained from national-level databases. For the three tillage options, probabilities were derived from the Crop Residue Management Survey, which is a county-level database that reports the acres for each tillage type by crop (CTIC 2001). The probabilities for the commercial fertilizer application options were derived from the Cropping Practices Survey data by state and crop and were based on the number of observations (farmers surveyed) associated with each of the selected possibilities. The percentage of acres with manure applied as derived from the 1997 Census of Agriculture were used as the probabilities for options with manure applications, calculated for each state and climate zone combination. The probability that the manure was applied on a manure producing farm or on a manure receiving farm was obtained from the same source.

Table A–1 provides an example of how the NRI variable for nitrate loss in runoff was determined for URU 7462. Sprinkler irrigated corn is grown in this URU located in Nebraska within climate cluster 27, which encompasses the northwest portion of the state. The soil is a Blendon fine sandy loam and conservation practices (terraces, contour farming, and stripcropping) are not present. Nutrient management options based on the Cropping Practices database for Nebraska corn consisted of 21 nutrient application time and rate combinations for commercial fertilizer applications (specific options and probabilities of occurrence are shown in table 15 in the main body of the report) and two manure fertilizer options. The 23 nutrient management options were replicated for each of the three tillage systems—conventional-till, mulch-till, and no-till—resulting in a total of 69 management options for the URU. Each management option requires a unique set of field operations to simulate the management option using EPIC. (An example set of field operations for one of the 69 management systems is shown in table 10 in the main body of the report.) Probabilities associated with each tillage type, each manure option, and each commercial fertilizer option are shown in table A–1. The joint probability for the management system is the multiple of the three probabilities, also shown in table A–1. The weighted model output is then calculated for each of the 69 model runs (shown in the last column in table A–1) and summed to obtain the weighted average for the URU. As shown in the last row of table A–1, the weighted estimate of average annual nitrogen lost in runoff is 4.52 pounds per acre for this example. This value was then assigned to each of the 5 NRI sample points associated with this URU.

All model results were calculated in this same manner for each URU and assigned to NRI cropland sample points associated with each URU.

Table A–1 Example of how EPIC-generated variables were estimated for NRI cropland sample points

Tillage	Application time	Fertilizer application rate		Manure application	Average annual nitrogen lost in runoff (lb/a)*	Commercial fertilizer option probability	Manure application option probability	Tillage option probability	Joint probability of management system	Weighted model output for nitrogen runoff
Conventional	Fall	High N	Average P	No manure	6.45	0.0173	0.8921	0.5066	0.00782	0.0504
Conventional	Spring	High N	Average P	No manure	8.48	0.0370	0.8921	0.5066	0.01672	0.1418
Conventional	Fall and at plant	High N	Average P	No manure	6.65	0.0379	0.8921	0.5066	0.01713	0.1140
Conventional	Spring and at plant	High N	Average P	No manure	7.81	0.0864	0.8921	0.5066	0.03905	0.3048
Conventional	At plant and after plant	High N	Average P	No manure	14.50	0.0996	0.8921	0.5066	0.04502	0.6528
Conventional	Fall	High N	Zero P	No manure	6.45	0.0123	0.8921	0.5066	0.00556	0.0359
Conventional	Spring	High N	Zero P	No manure	5.22	0.0428	0.8921	0.5066	0.01934	0.1010
Conventional	Fall	Medium N	Average P	No manure	6.04	0.0099	0.8921	0.5066	0.00447	0.0270
Conventional	Spring	Medium N	Average P	No manure	5.50	0.0379	0.8921	0.5066	0.01713	0.0942
Conventional	Fall and at plant	Medium N	Average P	No manure	4.92	0.0428	0.8921	0.5066	0.01934	0.0952
Conventional	Spring and at plant	Medium N	Average P	No manure	5.47	0.0864	0.8921	0.5066	0.03905	0.2135
Conventional	At plant and after plant	Medium N	Average P	No manure	6.22	0.1012	0.8921	0.5066	0.04574	0.2847
Conventional	Fall	Medium N	Zero P	No manure	6.65	0.0263	0.8921	0.5066	0.01189	0.0790
Conventional	Spring	Medium N	Zero P	No manure	2.43	0.0395	0.8921	0.5066	0.01785	0.0434
Conventional	Fall	Low N	Average P	No manure	1.54	0.0132	0.8921	0.5066	0.00597	0.0092
Conventional	Spring	Low N	Average P	No manure	2.06	0.0247	0.8921	0.5066	0.01116	0.0230
Conventional	Fall and at plant	Low N	Average P	No manure	2.39	0.0370	0.8921	0.5066	0.01672	0.0399
Conventional	Spring and at plant	Low N	Average P	No manure	2.54	0.0872	0.8921	0.5066	0.03941	0.1003
Conventional	At plant and after plant	Low N	Average P	No manure	2.16	0.0955	0.8921	0.5066	0.04316	0.0930
Conventional	Fall	Low N	Zero P	No manure	1.42	0.0189	0.8921	0.5066	0.00854	0.0121
Conventional	Spring	Low N	Zero P	No manure	1.24	0.0461	0.8921	0.5066	0.02084	0.0258
Conventional	At plant	Derived		Manure producer	0.87	1.0000	0.0276	0.5066	0.01400	0.0122
Conventional	At plant	Derived		Manure receiver	1.42	1.0000	0.0803	0.5066	0.04069	0.0580
Mulch	Fall	High N	Average P	No manure	5.70	0.0173	0.8921	0.2787	0.00430	0.0245
Mulch	Spring	High N	Average P	No manure	8.22	0.0370	0.8921	0.2787	0.00920	0.0757
Mulch	Fall and at plant	High N	Average P	No manure	5.73	0.0379	0.8921	0.2787	0.00942	0.0540
Mulch	Spring and at plant	High N	Average P	No manure	6.87	0.0864	0.8921	0.2787	0.02148	0.1476
Mulch	At plant and after plant	High N	Average P	No manure	14.46	0.0996	0.8921	0.2787	0.02476	0.3582
Mulch	Fall	High N	Zero P	No manure	5.53	0.0123	0.8921	0.2787	0.00306	0.0169
Mulch	Spring	High N	Zero P	No manure	3.90	0.0428	0.8921	0.2787	0.01064	0.0415
Mulch	Fall	Medium N	Average P	No manure	5.24	0.0099	0.8921	0.2787	0.00246	0.0129
Mulch	Spring	Medium N	Average P	No manure	4.20	0.0379	0.8921	0.2787	0.00942	0.0395
Mulch	Fall and at plant	Medium N	Average P	No manure	4.13	0.0428	0.8921	0.2787	0.01064	0.0440

Table A–1 Example of how EPIC-generated variables were estimated for NRI cropland sample points—Continued

Tillage	Application time	Fertilizer application rate		Manure application	Average annual nitrogen lost in runoff (lb/a)*	Commercial fertilizer option probability	Manure application option probability	Tillage option probability	Joint probability of management system	Weighted model output for nitrogen runoff
Mulch	Spring and at plant	Medium N	Average P	No manure	4.38	0.0864	0.8921	0.2787	0.02148	0.0942
Mulch	At plant and after plant	Medium N	Average P	No manure	5.25	0.1012	0.8921	0.2787	0.02516	0.1321
Mulch	Fall	Medium N	Zero P	No manure	6.03	0.0263	0.8921	0.2787	0.00654	0.0394
Mulch	Spring	Medium N	Zero P	No manure	1.69	0.0395	0.8921	0.2787	0.00982	0.0166
Mulch	Fall	Low N	Average P	No manure	1.04	0.0132	0.8921	0.2787	0.00328	0.0034
Mulch	Spring	Low N	Average P	No manure	1.36	0.0247	0.8921	0.2787	0.00614	0.0084
Mulch	Fall and at plant	Low N	Average P	No manure	1.85	0.0370	0.8921	0.2787	0.00920	0.0170
Mulch	Spring and at plant	Low N	Average P	No manure	2.02	0.0872	0.8921	0.2787	0.02168	0.0438
Mulch	At plant and after plant	Low N	Average P	No manure	2.29	0.0955	0.8921	0.2787	0.02375	0.0543
Mulch	Fall	Low N	Zero P	No manure	0.92	0.0189	0.8921	0.2787	0.00470	0.0043
Mulch	Spring	Low N	Zero P	No manure	0.83	0.0461	0.8921	0.2787	0.01146	0.0095
Mulch	At plant	Derived		Manure producer	0.80	1.0000	0.0276	0.2787	0.00770	0.0062
Mulch	At plant	Derived		Manure receiver	1.32	1.0000	0.0803	0.2787	0.02238	0.0296
No-till	Fall	High N	Average P	No manure	2.32	0.0173	0.8921	0.2147	0.00331	0.0077
No-till	Spring	High N	Average P	No manure	6.83	0.0370	0.8921	0.2147	0.00709	0.0484
No-till	Fall and at plant	High N	Average P	No manure	2.36	0.0379	0.8921	0.2147	0.00726	0.0171
No-till	Spring and at plant	High N	Average P	No manure	3.74	0.0864	0.8921	0.2147	0.01655	0.0619
No-till	At plant and after plant	High N	Average P	No manure	13.17	0.0996	0.8921	0.2147	0.01908	0.2512
No-till	Fall	High N	Zero P	No manure	2.27	0.0123	0.8921	0.2147	0.00236	0.0053
No-till	Spring	High N	Zero P	No manure	1.32	0.0428	0.8921	0.2147	0.00820	0.0108
No-till	Fall	Medium N	Average P	No manure	1.89	0.0099	0.8921	0.2147	0.00190	0.0036
No-till	Spring	Medium N	Average P	No manure	1.32	0.0379	0.8921	0.2147	0.00726	0.0096
No-till	Fall and at plant	Medium N	Average P	No manure	1.44	0.0428	0.8921	0.2147	0.00820	0.0118
No-till	Spring and at plant	Medium N	Average P	No manure	2.00	0.0864	0.8921	0.2147	0.01655	0.0332
No-till	At plant and after plant	Medium N	Average P	No manure	2.47	0.1012	0.8921	0.2147	0.01938	0.0479
No-till	Fall	Medium N	Zero P	No manure	6.33	0.0263	0.8921	0.2147	0.00504	0.0319
No-till	Spring	Medium N	Zero P	No manure	0.58	0.0395	0.8921	0.2147	0.00757	0.0044
No-till	Fall	Low N	Average P	No manure	0.74	0.0132	0.8921	0.2147	0.00253	0.0019
No-till	Spring	Low N	Average P	No manure	0.67	0.0247	0.8921	0.2147	0.00473	0.0032
No-till	Fall and At Plant	Low N	Average P	No manure	1.18	0.0370	0.8921	0.2147	0.00709	0.0084
No-till	Spring and at plant	Low N	Average P	No manure	1.30	0.0872	0.8921	0.2147	0.01670	0.0217
No-till	At Plant and after plant	Low N	Average P	No manure	1.49	0.0955	0.8921	0.2147	0.01829	0.0272

Table A–1 Example of how EPIC-generated variables were estimated for NRI cropland sample points—Continued

Tillage	Application time	Fertilizer application rate		Manure application	Average annual nitrogen lost in runoff (lb/a)*	Commercial fertilizer option probability	Manure application option probability	Tillage option probability	Joint probability of management system	Weighted model output for nitrogen runoff
No-till	Fall	Low N	Zero P	No manure	0.59	0.0189	0.8921	0.2147	0.00362	0.0021
No-till	Spring	Low N	Zero P	No manure	0.40	0.0461	0.8921	0.2147	0.00883	0.0036
No-till	At plant	Derived		Manure producer	0.68	1.0000	0.0276	0.2147	0.00593	0.0040
No-till	At plant	Derived		Manure receiver	0.99	1.0000	0.0803	0.2147	0.01724	0.0170
		Totals for URU 7462							1.00	4.52

* Average of 30 annual estimates obtained for each of the 69 EPIC model simulations.

Appendix B Summary of EPIC application and performance literature

The complexity of the natural environment modeled by EPIC and the comprehensive accounting of soil and weather properties and management alternatives allowed by the model preclude any simple summary statement about the prediction error of EPIC model output. Validating environmental effects such as nutrient leaching and runoff is difficult because these and other endpoints are seldom measured at the field level. Actual weather events, which drive the model outputs, are highly variable, further complicating validation efforts. A complete validation of EPIC would require that field-level measurements be taken on a variety of soil types in several climatic zones, each with several crops grown using a variety of production technologies. Moreover, the validation study would need to be repeated each time the model was updated. The cost of conducting such a study is clearly prohibitive.

Over the years, however, various researchers have conducted partial validation studies in conjunction with the study of specific issues. There are more than 150 journal articles and reports documenting the use of EPIC in a wide variety of situations. Results from a selection of these studies are listed in table B–1. Findings from some of these studies are summarized below. It is important to note that these studies were for older versions of EPIC than used in the present study.

Williams et al. (1989) evaluated EPIC's ability to simulate yields of maize, wheat, rice, sunflower, barley, and soybeans using a total of 227 measured yields reported by independent research groups around the world. For these crops, mean simulated yields were within 7 percent of mean measured yields. For 118 comparisons of measured and simulated maize yields, mean measured yield and its standard deviation were 103 bushels per acre and 49 bushels per acre, respectively. The measured and simulated means were not significantly different at the 95 percent confidence level. This study also demonstrated that EPIC can accurately simulate maize responses to irrigation at locations in the western United States and to nitrogen fertilizer in Hawaii.

Dyke et al. (1990) compared simulated and measured yields for a total of 204 treatment years for the Southern Coastal Plain and Southern High Plains of Texas. Crops included maize, grain sorghum, and cotton. Tillage systems, irrigation, and crop rotations also varied. Simulated yields were within 20 percent of mean measured yields for 70 and 90 percent of treatment-years for the Coastal Plain and High Plains, respectively. Simulated yields were within the 95 percent confidence interval of measured yields for 69 and 88 percent of the treatment-years for the two sites.

Bryant et al. (1992) examined the ability of the EPIC model to simulate the controlled field experiments on the impact of alternative irrigation management strategies on corn yields for corn grown in the Southern High Plains. Data for comparison to model results was for the period of 1975–1977. Bryant et al. found that the mean of simulated yields was not significantly different (P=0.05) from the mean of the measured yields. The standard deviation of simulated yields exceeded that of measured yields. Yield trends over the period were similar. The EPIC model was able to explain from 72 to 86 percent of the variance in measured yields depending on the year of comparison.

Cabelguenne et al. (1990) evaluated the ability of EPIC to simulate the effects of management of complex crop rotations in southern France, including the effects of irrigation, nitrogen fertilization, and the previous crop on crop growth and yield. For three levels of fertilizer application and a complex four-crop rotation, the differences between simulated yields and measured yields varied from 1 to 17 percent depending on the year, crop, and the fertilizer level.

Chung et al. (1999) validated EPIC against measured hydrologic and environmental quality indicators for two tillage systems (conventional and ridge till) in two watersheds in Southwest Iowa that had been under continuous corn cropping. The model was first calibrated using 1988 to 1994 data for surface runoff, seepage flow, and evapotranspiration (ET), and then validated for those variables plus NO_3 losses, soil erosion, and crop yields using 1976–1987 data. The percent errors for the EPIC model simulations are summarized:

	Watershed 1	**Watershed 2**
Validation period (1976–1987)		
Surface runoff	+2.1%	+0.2%
Seepage flow	+10.0	-3.2
ET	-0.6	+1.3
NO_3-N leached	-8.8	+4.7
NO_3-N runoff	+43.8	0.0
Crop yield	+4.1	-1.3

Edwards et al. (1994) tested the ability of the EPIC model to simulate non-point source pollution arising from the application of animal waste to agricultural land in Arkansas (four pasture fields). Model predictions of runoff, sediment yield, nitrate losses, organic N losses, soluble P losses, and total P (TP) losses were compared with measured data over a 20-month period and model performance was assessed both for storm events and on a calendar year basis. The correlation between observed and predicted events was significant (P=0.05) for each field. Observed and predicted event TP were significantly correlated for three fields, and there was a significant correlation between observed soluble P and sediment losses for two fields. The overall performance of EPIC on a calendar year basis was very good for all parameters except nitrate losses.

The ability of EPIC to simulate soil carbon changes due to land use and crop management changes was tested by Izaurralde et al. (2001) by comparing actual field test plot measurements to EPIC model results for the same situations. For five sites where cropland had been converted to perennial grass cover in the CRP program in Kansas, Nebraska, and Texas, the EPIC estimate of final soil organic carbon ranged from 80.7 to 139.5 percent of the observed measured value. For a 60-year wheat/fallow rotation experiment at Breton, Canada, the EPIC estimate of soil carbon ranged from 89.5 to 105.6 percent of observed for the control treatment, 93.6 to 199.3 percent of observed for the applied fertilizer treatment, and 74.7 to 99.4 percent of observed for the manured treatment.

Wang et al. (2005) conducted the sensitivity and uncertainty analyses of corn yields and soil organic carbon (SOC) simulated with the EPIC for a 34-year experiment at the University of Wisconsin Arlington Agricultural Research Station in south central Wisconsin. The long-term experiment was established in 1958 with the purpose of evaluating the response of continuous corn to different N fertilization treatments (Vanotti et al., 1997). The study demonstrated EPIC is dependable and accurate from a statistical point of view in simulating corn yields and SOC. The measured average corn yields fell well within the 5 percent and 95 percent confidence limits. The width of 90 percent confidence interval bands for corn yields ranged from 0.31 to 1.6 milligauss hectare^{-1}, while predicted and observed means were 3.26 to 6.37 milligauss hectare^{-1} and 3.28 to 6.4 milligauss hectare^{-1}, respectively, for the 5 nitrogen treatments. The 90 percent confidence width for SOC was 0.97 to 2.13 gram kilogram^{-1}, while predicted means and observed SOC were 17.4 to 22.3 gram kilogram^{-1} and 19.2 to 22.9 gram kilogram^{-1}, respectively. The optimal parameter set for the study site gave an R^2 of 0.96 for mean corn yield predictions, with errors ranging from -8.5 to 8.2 percent, and an R^2 of 0.89 for yearly SOC predictions, with errors ranging from -8.3 to 2.4 percent.

King et al. (1996) applied the EPIC model to estimate runoff, sediment yield, nutrient transport, and crop growth for six small watersheds for which measured data was available. Crop yield predictions were in the range of observed values for the region. The comparison for environmental quality indicators was as follows:

	Measured	**EPIC**
Runoff to precipitation ratio	12.99–19.89%	13.84–17.8%
Sediment loss—no-till	0.19 ton/ha	0.16 ton/ha
Sediment loss—conventional till	1.87 ton/ha	1.92 ton/ha
NO_3-N in runoff—no-till	3.15 kg/ha	3.43 kg/ha
NO_3-N in runoff—conventional till	6.60 kg/ha	5.43 kg/ha

Kiniry et al. (1997) tested the ability of the ALMANAC version of EPIC and a similar model to simulate long-term mean corn yields for one county in each of the following nine states (MN, NY, IA, IL, NE, MO, KS, LA, and TX). For each county, simulated corn grain yields for representative soil, weather, and management situations were compared to the county average yield for the period 1983 to 1992 as reported by the National Agricultural Statistics Service. Kiniry et al. reported that “Mean simulated grain yield for each county was always within 5 percent of the mean measured grain yield for the location. Within locations, measured grain yield was regressed on simulated grain yields and tested to see if the slope was significantly different from 1.0 and if the y-intercept was significantly different from 0.0, both at the 95 percent confidence level.” For the EPIC version, the slope or the intercept was significantly different from the hypothesized values only for Minnesota, New York, and Nebraska, and the coefficient of variation of simulated grain yields were similar to those of measured yields at most sites.

A recent paper by Gassman et al. (2004) reviews the historical development and applications of the EPIC model.

Table B–1 Summary of selected EPIC application, evaluation, and validation studies

Author	Year	Focus	Scope
Hajek and Williams	1987	Erosion productivity effects	AL Coastal Plain and TN Valley
Williams et al.	1989	Yields: evaluation of EPIC crop growth sub-model	Barley, corn, rice, sorghum, sunflower, and wheat, various location in United States and France
Williams	1990	A case history of early EPIC development	Not applicable
Cabelguenne et al.	1990	Yield calibration and validation for rotations	Southern France
Bryant et al.	1992	Yield response to irrigation	Corn in the Southern Plains
Kiniry et al.	1992	Yield calibration for sunflowers	Toulouse, France
Cabelguenne et al.	1993	Irrigation strategy optimization	Corn in SW France
Wallis, T. W. R.	1993	Weather simulator	Five TX locations
Nicks et al.	1994	Erosion prediction equation alternatives	Twenty-two sites across the U.S.
Edwards et al.	1994	Runoff transport of surface applied nutrients	Field level – NW AR forage fields
Potter and Williams	1994	Soil temperature, daily prediction	IA, ND, and TX sites
Sloot et al.	1994	Alternative tillage systems	Secano Interior of Chile
Easterling et al.	1996	Climate change effect, validation of yield response	Seven weather stations in E. NE
King et al.	1996	Sediment and nitrate loss with conservation tillage	Vertisol Blackland Prairie in Central TX
Purveen et al.	1996	Snowmelt and water erosion	Peace River region of Alberta
Kiniry et al.	1997	Yield estimate comparison for corn and other model	Nine locations across the U.S.
Ramanarayanan et al.	1998	Runoff and soil loss	Small watersheds in OK and TX
Chung et al.	1999	Non-point source pollutant loading	Watershed in SW IA
Cavero et al.	Late 90s	Nitrogen cycling in vegetable-grain cropping systems	
Chen et al.	2001	Non-point source water quality	Trinity River Basin in TX
Izaurralde et al.	2001	Soil carbon	Scaling point estimates up to regional and national (U.S. sites)
Izaurralde et al.	2001	Soil carbon, tillage and cover	Canadian and U.S. field plot studies
Tan and Shibasaki	2003	Global warming and crop productivity	Global – various countries and crops
Perez et al.	2003	Yields with precision farming	CA crop and vegetable rotations