doi:10.2489/jswc.69.1.26

Nutrient delivery from the Mississippi River to the Gulf of Mexico and effects of cropland conservation

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Abstract: Excessive nutrients transported from the Mississippi River Basin (MRB) have created a hypoxic zone within the Gulf of Mexico, with numerous negative ecological effects. Furthermore, federal expenditures on agricultural conservation practices have received intense scrutiny in recent years. Partly driven by these factors, the USDA Conservation Effects Assessment Project (CEAP) recently completed a comprehensive evaluation of nutrient sources and delivery to the Gulf. The modeling framework used in the CEAP Cropland National Assessment, or Cropland CEAP, consists of the Agricultural Policy/Environmental eXtender (APEX) and Soil and Water Assessment Tool (SWAT) models. This CEAP modeling framework was successfully calibrated for flow, sediment, and nutrients at 38 sites and validated at an additional 17. Simulation results indicated that cultivated cropland was the dominant source of nitrogen (N) and phosphorus (P) to both local waters and the Gulf, but this was not true for each water resource region within the MRB. In addition, the results showed that point sources remain significant contributors of P loads, especially in the Tennessee and Arkansas/Red River basins where point source P loads exceeded those from cultivated cropland. Similarly, urban nonpoint sources were significant nutrient sources. The Upper Mississippi, Lower Mississippi, and Ohio basins contributed the largest amounts of nutrients delivered to the Gulf. The high delivery areas near the Mississippi River main stem, from which 87% of N and 90% of P was predicted to reach the Gulf, also coincided with elevated nutrient yields to local waters. Conservation practices established on agricultural lands within the MRB were predicted to have reduced nutrient loads to the Gulf by 20% as compared with a no conservation condition. The results indicate the importance of targeted implementation of conservation practices and consideration of local water and/or Gulf impacts depending on program goal(s). The present application illustrates the value of the Cropland CEAP modeling framework as a useful, science-based tool to evaluate pollutant sources and delivery and effects of agricultural conservation practices.

Key words: conservation—Conservation Effects Assessment Project—Gulf of Mexico—Soil and Water Assessment Tool—Mississippi—nutrient

Following the Government and Performance Act of 1993, the USDA is required to provide scientifically credible estimates of the environmental benefits of federal expenditures. The Office of Management and Budget and congressionally-mandated Conservation Effects Assessment Project (CEAP) was initiated by the USDA in 2003 to quantify the benefits of US agricultural conservation expenditures. The project was originally established in response to an 80% increase in conservation spending associated with the 2002 Farm Bill (Mausbach and Dedrick 2004). By 2008, conservation title spending by the federal government had grown to US$3.7 billion per year (Monke and Johnson 2010).

One important component of CEAP is the CEAP Cropland National Assessment, or Cropland CEAP, which focuses on the fate and transport of sediment, nutrients, and pesticides from cultivated cropland to US waters. These cultivated lands are dispersed throughout the landscape; therefore, the entire landscape must be considered if hydrologic and water quality models are used to predict the delivery of sediment and nutrients. Similarly, the contribution of other sources (including noncultivated lands, urban areas, forests, and the direct discharge of waste water to streams and rivers) should be accounted for. In addition, processes occurring in streams, lakes, and reservoirs affect the fate of pollutants as they are transported through the system and should also be included.

Comprehensive water quality simulation at the scale of the Mississippi River Basin (MRB, 3,220,000 km^2 [1,240,000 mi^2]) is a difficult task; thus, only a few modeling efforts at that scale have been conducted to date. The contiguous United States was simulated by Srinivasan et al. (1998) in the Hydrologic Unit Model for the United States (HUMUS) project using the Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998). HUMUS is a combination of predictive models; Geographic Information System (GIS) tools and spatial data; and relational databases with climate, soil, and management data. The HUMUS project was conducted to assess the impacts and risks of management alternatives on regional water resources, and its framework and databases were used for portions of the Cropland CEAP models described within.

Other national (Smith et al. 1997) and regional scale (Garcia et al. 2011; Anning 2011; Rebich et al. 2011) modeling efforts have used the US Geological Survey (USGS) SPAtially Referenced Regressions On Watershed attributes (SPARROW) model (Smith et al. 1997),

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which was designed to extrapolate existing water quality information to areas deficient in monitoring data. SPARROW has been used at both national and regional scales to predict nutrient and sediment delivery from the landscape though streams, rivers, and impoundments. Alexander et al. (2008) used SPARROW to predict the relative contributions of various sources within the MRB. They found that 66% of nitrogen (N) and 43% of phosphorus (P) originated from cultivated cropland and that grasslands contributed 5% of N and 37% of P reaching the Gulf. The SPARROW model predicted in-stream/reservoir nutrient retention to be greater in the central and eastern portions of the MRB (50% to 75%) than in the western portions (25% to 50%). Urban sources including both point and nonpoint sources accounted for 9% and 12% of N and P, respectively.

Other researchers have predicted the contribution of urban point sources within the MRB. Tetra Tech (1998) estimated the total N and P loads from all point sources to be 291 million kg y^{-1} (641 million lb yr^{-1}) and 60 million kg y^{-1}(132 million lb yr^{-1}), respectively, based on 1996 data; however, the US Environmental Protection Agency (USEPA) Management Action Reassessment Team (MART) (2006) estimated much lower annual loads (211 million kg N [465 million lb N], 35 million kg P [77 million lb P]) based on 2004 data. USEPA (2007) further revised the estimates to 267 million kg of N (588 million lb of N) and 53 million kg of P (117 million of P) annually using MART (2006) data and differing estimates for typical pollutant concentrations. USEPA (2007) also estimated the total contribution of point sources to the Gulf of Mexico to be 22% and 34% of N and P, respectively. These loads are considerably larger than those estimated by SPARROW for point sources and nonpoint urban sources combined (Alexander et al. 2008). However, unlike SPARROW, these estimates do not consider in-stream losses and should be considered an upper estimate of the contribution to riverine loads (USEPA 2007). The relatively large fraction of P loads from point sources is notable since the USEPA (2007) found that primary algal production in the near shore area of rivers and streams was limited by P during the spring. These point source estimates are subject to considerable uncertainty due to limited facility discharge and concentration information upon which they are based. Of the 32,416 permitted facilities in the MRB assembled by MART (2006), only 1,248 (4%) have flow and nutrient concentration records, which allow for an accurate estimate of total load, and 6,907 (21%) have only measured flow requiring that pollutant concentrations be estimated. In addition, 12,918 (39%) have a design flow only, and 11,343 (34%) have no reported design flow, requiring that both flow and concentration be estimated. Regional pollutants from all sources within the MRB were also predicted by Goolsby et al. (1999) for 1980 to 1996 using measured data and regression models. They found that the Upper Mississippi Basin was responsible for 33% and 19% of total N and P, respectively. The Ohio (including the Tennessee) basins generated 32% and 29% of the Gulf N and P load, respectively, and the Missouri River Basin N and P contributions were 15% and 19%, respectively. The location of major river basins within the MRB is depicted in figure 8.

Cropland CEAP is a multistage research effort with regional simulations and peer reviewed reports developed for each of six two-digit US Geological Society (USGS) hydrologic units within the MRB. Reports were published for the Ohio/Tennessee, Missouri, and Upper Mississippi River basins (USDA NRCS 2010, 2011, 2012). These reports underwent peer review prior to release and detail the development and application regionally calibrated/validated Agricultural Policy/Environmental eXtender (APEX) (Williams and Izaurralde 2006) and SWAT models. Methods, protocols, data sources, and results are described in detail in cited references, thus they are discussed only briefly as needed in the present manuscript. The reports for the Lower Mississippi and the Arkansas/Red River basins have not yet been released; however, the simulations are complete. Research presented herein combines these regional simulation efforts into a single framework applicable across the entire MRB. This combined CEAP framework for the MRB was subjected to additional validation and analysis of noncropland sources. An additional analysis of nutrient delivery through the entire river system to the Gulf was conducted to place regional CEAP predictions in the proper context. The intent was to utilize the CEAP framework to examine nutrient sources within the MRB as a whole and delivery to the Gulf of Mexico not duplicate results from regional modeling reports. More specifically, the primary study objectives were to use the CEAP modeling framework (i.e., combined APEX/SWAT models) to (1) characterize nutrient (N and P) yield from the landscape at the eight-digit basin scale to local waters, (2) predict the delivery of N and P from local waters through the MRB to the Gulf of Mexico, (3) determine the relative contribution of pollutant sources both categorically and spatially, and (4) assess the total nutrient load reduction due to establishment of structural and cultural conservation practices within the MRB.

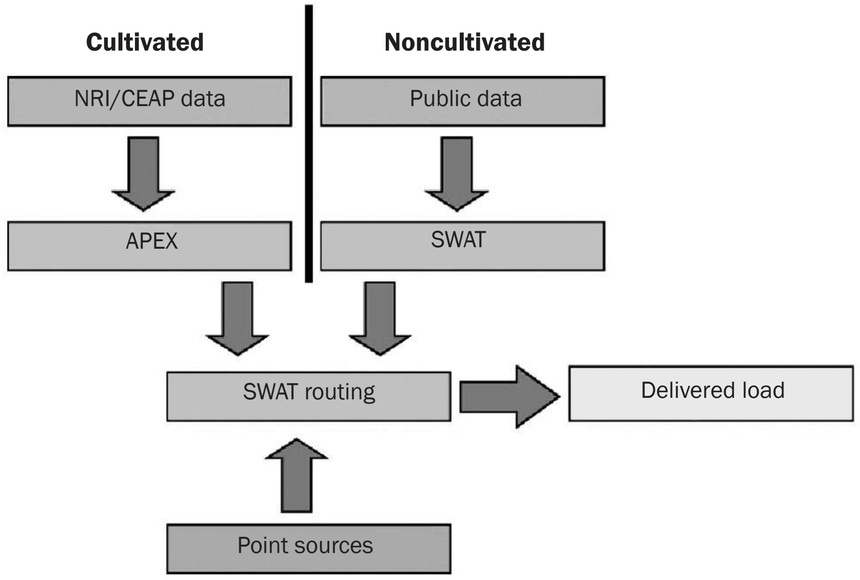
Materials and Methods

Conservation Effects Assessment Project Modeling Framework. The CEAP modeling framework depicted in figure 1 utilized two simulation models within the existing national HUMUS framework, APEX and SWAT. Both models are distributed hydrologic and water quality models which operate on a daily time step. They are widely used to predict pollutant fate and transport from the landscape (Gassman et al. 2007, 2010) and consist of process-based routines that simulate major hydrologic, sediment, and nutrient fate processes. The primary difference between APEX and SWAT is scale of applicability and complexity.

Agricultural Policy/Environmental eXtender and Soil and Water Assessment Tool Description and Integration. APEX was developed to assess the impacts of management on environmental and production issues at the field or small watershed level. The model is an evolution of the Environmental Policy Integrated Climate (EPIC) model, which was developed as a homogeneous single field model (Williams et al. 1980). EPIC in turn was derived from the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Leonard et al. 1987), and Simulator for Water Resources in Rural Basins (SWRRB) (Williams et al. 1985) models and utilizes code and concepts from many other predictive tools and models of the time. APEX is versatile and can simulate a wide variety of processes related to conservation management and structural practices, including irrigation, drainage, furrow diking, buffer strips, terraces, grassed waterways, fertilizer application, manure application, crop rotation, grazing, pesticide use, and tillage operations (Williams and Izaurralde 2006).

Figure 1

Conservation Effects Assessment Project (CEAP) modeling framework, including the National Resources Inventory (NRI), Agricultural Policy/Environmental eXtender (APEX), and the Soil and Water Assessment Tool (SWAT).



SWAT is less complex and thus easier to parameterize, making it more applicable for simulating large basins (Gassman et al. 2007; Douglas-Mankin et al. 2010; Tuppad et al. 2011). Major SWAT processes include rainfall/runoff, plant growth, soil nutrient dynamics, and pollutant losses. SWAT also contains in-stream and reservoir sub models derived from ROTO (Arnold et al. 1995) and QUAL2E (Brown and Barnwell 1987). These components are critical in the prediction of pollutant delivery in large river basins.

For this study, edge-of-field runoff, sediment, and nutrient losses from cultivated cropland were predicted using the APEX model. APEX is well-suited for this application as parameterization data are relatively abundant at surveyed fields and the scale is small. Other land uses, in-stream processes, and trapping of pollutants in impoundments were simulated using the SWAT model. SWAT was more suited for this application as the scale is large and parameterization data are more limited. Other research has used SWAT and APEX integrated within as single modeling framework (Saleh et al. 2003; Saleh and Gallego 2007). This approach offers the advantage of using the more detailed APEX model where data are plentiful and SWAT where data are more limited. For this study, each of the 848 eight-digit Hydrologic Unit Codes (HUC8) (USGS 1994) in the MRB was treated as a subbasin within SWAT, and all predictions are presented at that HUC8 level. Additional detail concerning the integration of APEX and SWAT in Cropland CEAP is available in Wang et al. (2011a; 2011b) and Santhi et al. (2012).

Data Sources. Edge-of-field runoff volume, sediment, and nutrient loads from cultivated cropland were simulated by APEX using procedures described by Wang et al. (2011a; 2011b) for the period 1960 to 2007. These data were aggregated within each HUC8 to provide a single prediction of the total load delivered to the HUC8 outlet. The application of delivery ratios and integration of these data into SWAT are given in Wang et al. (2011a). Daily precipitation and temperature data were developed by Di Luzio et al. (2008) and provided interpolated estimates of single time series of precipitation and temperature for each HUC8. Soil data for cultivated fields were derived from the USDA Natural Resources Conservation Service National Soil Information System (USDA NRCS 2012). Management data, such as fertilization, tillage, planting, harvesting, and other field operations, were derived from survey data obtained directly from operator interviews from the National Resources Inventory CEAP Cropland Survey, which included ~20,000 samples nationwide (Goebel 2009). Methods for composing APEX inputs from these survey data are described by Atwood et al. (2009).

The SWAT model was used to simulate all portions of the landscape not represented in the APEX cultivated cropland simulations. This included other agricultural land such as pasture, hayland, and rangeland as well as nonagricultural sources including urban and point sources. SWAT was also used to predict the delivery of sediment, N, and P through streams, rivers, lakes, and reservoirs in route to the Gulf. A detailed description of these procedures and data sources is given by Arnold et al. (2010), Santhi et al. (2012), and each of the regional reports (USDA NRCS 2010, 2011, 2012).

A variety of data were used in CEAP modeling framework. Some data such as weather and atmospheric deposition of nutrients are common to both SWAT and APEX simulations. Topographic data were used to define the subbasin layout, and the stream network was derived from previous HUMUS efforts, which also used HUC8 boundaries as subbasins. Each subbasin in the MRB simulation framework had 40 to 99 subunits simulated as Hydrologic Response Units (HRUs) which represent a unique combination of soil, topography, and land use. The HRUs were derived by intersecting State Soil Geographic Database soils (USDA NRCS 1992), 2001 National Land-Cover Data Sets (Homer et al. 2007), and Hydrologic Landscape Regions of the United States (USGS 2003). The resulting overlay contained hundreds of thousands of unique combinations which were then aggregated into a smaller number of HRUs. The areal coverage of each unique combination was compared to percentage thresholds by landuse type. Any unique combination exceeding the threshold for that particular land-cover was defined as an HRU. These thresholds ranged from 1% for widespread land-covers such as forest and range to 0.1% for smaller yet intensively managed types such as pastures receiving animal manure. At least one HRU of each land-cover type was represented in each HUC8, and all HRU sizes were adjusted to preserve the original land use distribution in each HUC8. This process was consistent across all regional simulations.

Management data for noncultivated land uses were developed by an expert panel of simulation modelers and USDA Natural Resources Conservation Service personnel at the HUC8 level. Manure application for grasslands was derived from agricultural census data by Kellogg and Moffitt (2011). Point source nutrient loads including municipal and industrial sources were derived from data developed by USGS for SPARROW (Alexander 1998). These data were updated to reflect changes in population density and aggregated to HUC8 boundaries. Reservoir structural data were derived from the National Inventory of Dams (USACE 2009) and from existing HUMUS data. Reservoir release data were obtained from various local sources.

Agricultural Policy/Environmental eXtender and Soil and Water Assessment Tool Calibration and Validation. Various limitations of SWAT and APEX related to processes, scale, and data utilized in CEAP are discussed by other researchers (Benaman et al. 2005; Garen and Moore 2005; Radcliff et al. 2009; Mednick 2010). As predictive models, both SWAT and APEX output responses contain uncertainty which can be reduced through application of appropriate calibration and validation procedures. For this study, the calibration and validation of APEX and SWAT were separate processes (figure 2). The calibration/validation for APEX is described by Plotkin et al. (2009) and Williams et al. (2010), and only a brief summary is presented herein. Williams et al. (2010) validated APEX using measured data at Riesel, Texas; Arlington, Wisconsin; and Treynor, Iowa, for runoff, nutrient losses, sediment yield, soil carbon (C), and crop yield. Plotkin et al. (2009) validated APEX at Tifton, Georgia, for runoff, tile drain flow, and pesticide losses.

The calibration process for SWAT and the overall CEAP modeling framework occurred in two stages; for a more complete description, see Wang et al. (2011a), Kannan et al. (2011), and Santhi et al. (2012). Upland hydrology (runoff and base flow from upland areas) was calibrated first followed by downstream measured stream flow and water quality at multiple locations (figure 3). The upland hydrology was calibrated using an automated heuristic calibration procedure developed by Kannan et al. (2008). The average upland water yield (sum of runoff, lateral, and groundwater contribution to streamflow) was calibrated to nationwide data presented by Gebert et al. (1987) for each HUC8. Baseflow was calibrated to data developed by Santhi et al. (2008), who interpolated and filtered baseflow from stream flow gages specifically for CEAP.

Monitoring data collected at 38 USGS stream gages (figure 3; table 1) were used to further calibrate SWAT and the CEAP modeling framework as a whole. These sites were selected based on location, drainage area, and the availability of flow, nutrient, and sediment data. Available flow and water quality data (total and soluble N, total and soluble P, and total suspended solids) for each site were assembled and reviewed; at least 50 samples were required for consideration. Sites without sampling under a wide range of flow conditions (both base flow and storms) were rejected. These data were used to estimate annual pollutant flux using the USGS software LOADEST (Runkel et al. 2004) for the period 1960 to 2006 when possible. LOADEST uses the rating curve approach to derive empirical load models from discrete samples and daily streamflow. The empirical models were inspected and adjusted as needed to provide the most valid load estimates as defined by the residual variance between estimated and predicted concentration. At many sites, one or more constituents had insufficient data with which to develop a load estimate; thus those sites were not used for calibration for that constituent. Limited flow and water quality sampling data also restricted the comparison period for certain constituents at some sites.

For the Missouri, Ohio, and Tennessee River regions, SWAT was calibrated on an annual and monthly basis for flow and water quality using a manual calibration procedure detailed by Kannan et al. (2011) and Santhi et al. (2012). As methods and software improved with each subsequent regional calibration effort, the procedure was adapted and gradually automated. The resulting automated calibration software uses heuristic algorithms that alter SWAT inputs to improve calibration statistics. These heuristics are based on the experience gained in previous SWAT modeling efforts, including recommendations of model developers and experienced users. This software is intended to automate the decisions and tasks performed during an expert manual calibration. In addition to comparisons with measured data, the heuristics evaluate reservoir trapping, landscape per unit area loads, and in-stream delivery and then adjust model parameters as needed to maintain user-specified reasonable ranges for these processes. These parameter ranges were described in White et al. (2012); other regions in the MRB were also calibrated using this software.

The CEAP modeling framework (combined APEX/SWAT) was validated for the entire MRB using both measured data and the predictions of other large scale modeling efforts. The goal of validation is to determine whether the conceptual simulation model is an accurate representation of the system under study (Kleijnen 1995). Most often model validation is achieved by evaluating predictions against measured data not used in calibration or model development. Reckhow (1994) added the condition to validation that the data used is different in the sense that the important processes and forcing functions differ from the calibrated condition. Typically, available data are split into separate calibration and validation

Figure 2

Calibration/validation procedure used in the development of the Conservation Effects Assessment Program (CEAP) modeling framework. The procedure includes hydrologic unit code (HUC8), the Soil and Water Assessment Tool (SWAT), and SPAtially Referenced Regressions On Watershed attributes (SPARROW).

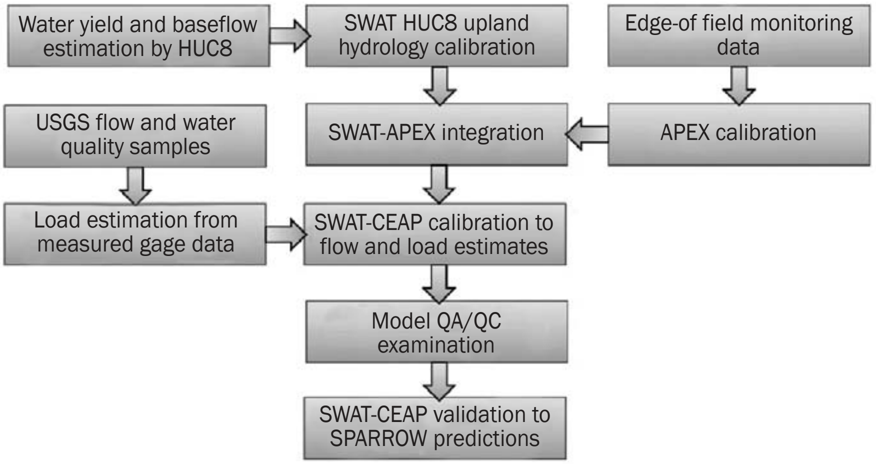
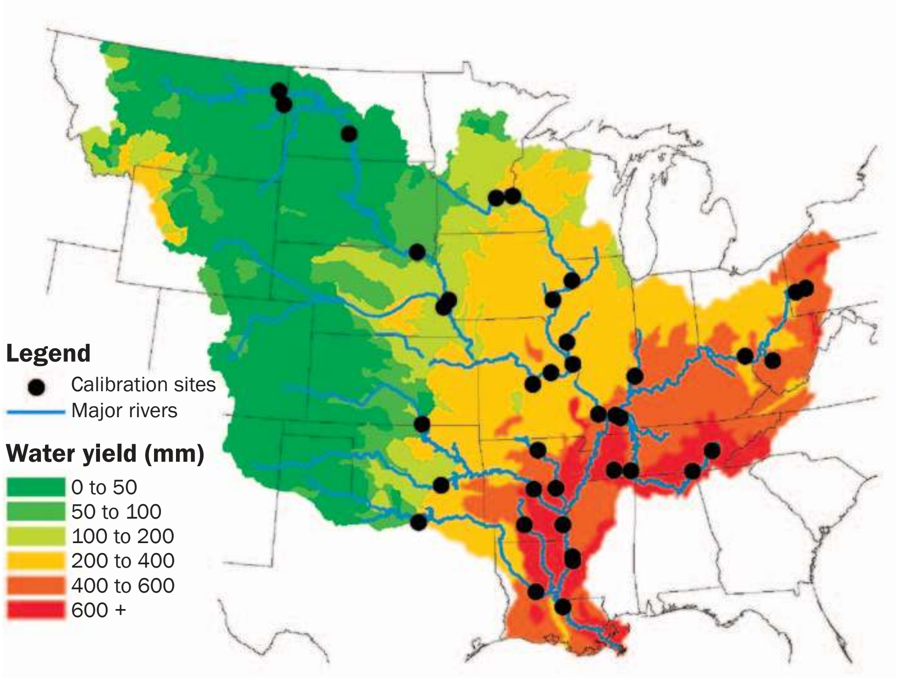


Figure 3

Water yield and stream gage locations for the Soil and Water Assessment Tool model calibration.



time-frames; the degree of independence between timeframes at a single site is debatable. Generally, the entire quality of both calibration and validation is judged by statistical metrics on a few model outputs with corresponding measured data. The validation presented herein augments traditional approaches with additional procedures to better evaluate if the model is a reasonable representation of the system.

Loads at 17 additional gage locations, selected based on location, drainage area, and sampling frequency (and not used in calibration), were used to validate the CEAP modeling framework (table 1) for the period 1970 to 2007. These load data were generated by Saad et al. (2011) using flow and discrete water quality sampling. Saad et al. (2011) developed and reported flow, total N, and total P at 2,700 sites across the United States. This dataset was not used in calibration as it contains only flow, total N, and total P; the calibration procedure utilized additional nutrient species. These data are based on sampling data collected from 1970 to 2007 although additional data outside this period was used when available. These data were detrended to the year 2002 to allow comparisons between sites with differing monitoring periods. Model predictions on an average annual basis were compared at each location.

The ability of a model to mimic measured data should not be the sole criteria by which it is validated. Models may produce results that appear reasonable because they mimic measured data with an acceptable statistical performance metric such as the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) or relative error (absolute error divided by measured value). The ability to mimic limited measured data is but a single piece of evidence that a model properly represents a system and is validated. As part of the validation, each regional model was analyzed using SWAT Check, a model screening tool developed to identify common model problems and unreasonable processes (White et al. 2012). This software compares plant growth, nutrient budgets, instream and reservoir processes, water balance, and nutrient loads by landuse type to literature values.

To further support the validation of the combined CEAP model, N and P predictions were compared with the SPARROW model on an average annual basis. SPARROW is a statistical model, which uses a variety of causal process factors such as soil properties, land use, and precipitation to predict in-stream nutrient loads and retention. SPARROW model coefficients are developed by calibrating to available water quality data. Comparisons of observed N and P data and SPARROW model predictions on an average annual basis allowed validation of the spatial distribution of nutrient loads throughout the system, a key issue in large river systems. SPARROW predicted loads were intended to represent condition in 1987 (Smith et al. 1997) which is near the midpoint of CEAP modeling framework general simulation period (1960 to 2006). As SPARROW was calibrated to measured data at a large number of sites, the estimated loads at the HUC8 level should be an excellent comparison for validation purposes. SWAT and SPARROW are very different models, developed for different purposes. The strength of SPARROW's statistical approach is the inclusion of a diversity of estimated loads at differing stream orders and local conditions. This complements the strengths of the SWAT and APEX models used in the CEAP modeling framework as process based models. These models are typically calibrated to less measured data, but their very detailed process-based nature allows accuracy to be maintained beyond the calibration conditions. The strength of this process-based approach lies in the ability of these models to simulate a variety of "what if" scenarios more robustly.

Effects of Established Conservation Practices. The effects of established conservation practices were isolated by exploring the differences between a modeling scenario representing current conservation practice conditions (described previously) and a second "no-practice" scenario representing conditions without the conservation practices reported by the CEAP survey. The no-practice scenario is not intended to exaggerate conservation effects by simulating a worst case scenario with excessive tillage and nutrient application or to simulate agriculture from the early 1900's with differing crop distribution and yields. Instead, this scenario is intended to simulate current conditions without a landowner conservation ethic or benefit from installing conservation practices. Details of how the existing APEX/SWAT simulations were modified to simulate a no-practice state are available in the regional CEAP reports (USDA NRCS 2010, 2011, 2012) and are not detailed here. The no-practice scenario was incorporated into APEX simulation for cultivated lands, and

Table 1

Calibration and validation sites used in the Conservation Effects Assessment Program modeling framework.

Calibration site	Eight-digit Hydrologic Unit Code	Drainage area (km^2)	Water quality samples	Period of record
Mississippi River near Arkansas City	8030100	2.92E+06	70	1961 to1980
Yazoo River near Long Lake	8030208	3.45E+04	274	1961 to 1976
Hatchie River at Bolivar	8010208	3.82E+03	82	1961 to 2006
White River at Devall's Bluff	8020301	6.04E+04	273	1961 to 2006
Ouachita River at Camden	8040102	1.38E+04	232	1961 to 2006
Mississippi River at Vicksburg	8060100	2.95E+06	146	1961 to2006
Mississippi River near St. Francisville	8070100	2.90E+06	280	1961 to 2006
White River at Calico Rock	11010004	2.57E+04	190	1961 to2006
Arkansas River at Arkansas City	11030013	1.13E+05	164	1961 to 2006
Canadian River near Calvin	11090202	7.21E+04	232	1961 to 2006
Red River at Gainesville	11130201	7.94E+04	215	1961 to 2006
Red River at Alexandria	8040301	1.74E+05	102	1972 to 2006
Arkansas River at Murray Dam	11110207	4.08E+05	207	1970 to 2006
Allegheny River at Natrona	5010009	2.94E+04	28	1961 to 2006
Ohio River at Sewickley	5030101	5.03E+04	80	1961 to 2006
Kanawha River at Charleston	5050008	2.70E+04	57	1961 to 2006
Ohio River near Greenup	5090103	1.60E+05	180	1969 to 2006
Wabash River at Mt. Carmel	5120113	7.39E+04	166	1961 to 2006
Ohio River at Metropolis	5140206	5.24E+05	53	1961 to 2006
Mississippi River at Hastings	7010206	9.57E+04	96	1996 to 2003
Illinois River at Valley City	7130011	6.90E+04	370	1961 to 2006
Iowa River at Wapello	7080209	3.23E+04	196	1961 to 2006
Minnesota River near Jordan	7020012	4.18E+04	230	1961 to 2006
Mississippi River at Clinton	7080101	2.21E+05	270	1961 to 2006
Mississippi River at Grafton	7110009	4.42E+05	183	1961 to 2006
Mississippi River at Thebes	7140105	1.84E+06	395	1961 to 2006
Platte River at Louisville	10200202	2.20E+05	302	1961 to 2006
Missouri River at Hermann	10300200	1.35E+06	430	1961 to 2006
Missouri River near Culbertson	10060005	2.36E+05	238	1961 to 2006
Missouri River at Yankston	10170101	7.21E+05	83	1976 to 1994
Missouri River at Omaha	10230006	8.33E+05	130	1961 to 2006
Osage River near St Thomas	10290111	3.74E+04	50	1961 to 1995
Missouri River at Bismark	10130101	4.81E+05	201	1961 to 2006
Yellowstone River near Sidney	10100004	1.78E+05	390	1961 to 2006
Tennessee River at Watts Bar Dam	6010201	4.47E+04	217	1961 to 1981
Tennessee River at Savannah	6040001	8.55E+04	47	196 1to 2004
Tennessee River near Paducah	6040006	1.04E+05	180	1974 to 2006
Tennessee River at South Pittsburg	6030001	5.84E+04	205	1974 to 1986
Validation site				
Missouri River at St. Joseph	10240011	1.08E+06	390	1970 to 2006
Missouri River at Sioux City	10230001	8.16E+05	40	1970 to 2006
Arkansas River at Terry L&D	11110207	4.09E+05	431	1970 to 2006
Ohio River near Smithland	5140203	3.72E+05	183	1970 to 2006
Mississippi River at Keokuk	7080104	3.08E+05	142	1970 to2006
Ohio River at Kosmosdale	5140101	2.36E+05	315	1970 to2006
Mississippi River at LD 9	7060001	1.66E+05	314	1970 to 2005
Platte River at Duncan	10200103	1.56E+05	159	1970 to 2006
Mississippi River at Winona	7040003	1.53E+05	112	1970 to 2006
Platte River near Grand Island	10200101	1.51E+05	258	1970 to 2006
Kansas River at Topeka	10270102	1.45E+05	235	1970 to 2006
Yellowstone River at Forsyth	10100001	1.03E+05	135	1977 to 2006
Red River near Terral	11130201	7.44E+04	260	1970 to 2006
Canadian River near Canadian	11090106	5.92E+04	296	1970 to 2006
Tennessee River near Chattanooga	6020001	5.48E+04	24	1974 to 2004
Des Moines River near Ottumwa	7100009	3.44E+04	86	1970 to 2006
Cumberland River at Cleese	5130202	3.30E+04	163	1970 to 2006

SWAT input parameters were not modified during scenario analysis.

Results and Discussion

Conservation Effects Assessment Project Modeling Framework Calibration. Calibration results for flow, sediment, N, and P at the 38 calibration sites are shown in figure 4. Since the dataset contains sites with tremendous differences in scale (eight-digit basins to sites 800 times larger draining nearly the entire Mississippi drainage area), log-log comparisons were used to allow all sites to be well represented regardless of scale. No universally accepted criteria, standards, or protocols for the evaluation of model performance exist. The most widely cited criteria (Moriasi et al. 2007) are intended for more typical applications where performance is evaluated at a few individual sites through time using metrics such as the NSE. Such comparisons at individual sites through time are given in the calibration/validation documentation for each Cropland CEAP regional APEX/SWAT model application (Kannan et al. 2011) and for the Ohio River basin by Santhi et al. (2012). In contrast, the comparisons presented within represent average annual values at a large number of sites, which differ substantially in drainage, data quality, and therefore, overall importance.

The CEAP modeling framework was calibrated for flow with relative errors ranging from −3.9% to 15.8% (median = −1.1%), and as expected, flow predictions were better than those for water quality, which required load estimation. Relative errors for sediment predictions ranged from −99% to 64% (median = 5.9%). Sites with larger confidence intervals as calculated by the LOADEST software were permitted to have larger relative error during calibration to avoid excess parameter adjustment. The site with the largest sediment relative error was the Kanawha River near Winfield, WV (USGS station 03201300). Total P was calibrated with relative errors ranging from −140% to 35% (median = −1.8%). The site with the largest relative error (−140%) was the Tennessee River near South Pittsburg, Tennessee (USGS station 03571850). Even though this site had the largest relative error, it also had the smallest absolute error in terms of mass of any site for total P. The model was calibrated for total N with a relative error ranging from −90% to 36% with a median of -0.8% across 38 sites. The largest relative error (-90%) at the Arkansas River at Arkansas City, Kansas (USGS station 07146500), could not be calibrated any closer to the estimated load without excessive parameter adjustment. It is not known whether this difference resulted from poor prediction or poor load estimation. Coefficient of determination (r^2) and NSE ranged from 0.98 to 0.99 across parameters (figure 4). These are not directly comparable to the criteria established by Moriasi et al. (2007) as these comparisons are across sites.

Conservation Effects Assessment Project Modeling Framework Validation. As with the calibration, the comparison of average annual loads at many sites is very different from comparisons through time at a single site, and commonly used metrics and criteria may not be applicable. Validation results are depicted in figure 5. Validation comparisons were somewhat less correlated as comparable calibration predictions, which is typical of modeling efforts. Comparisons with measured data support the validation in that the CEAP modeling framework is predicting flow and nutrient load adequately for its intended purpose on an average annual basis. Coefficient of determination values ranged from 0.82 to 0.98 and NSE ranged from 0.95 to 0.78. Predicted flow exhibited the best correlation and total P the worst, possibly due to the additional uncertainties in particulate transport.

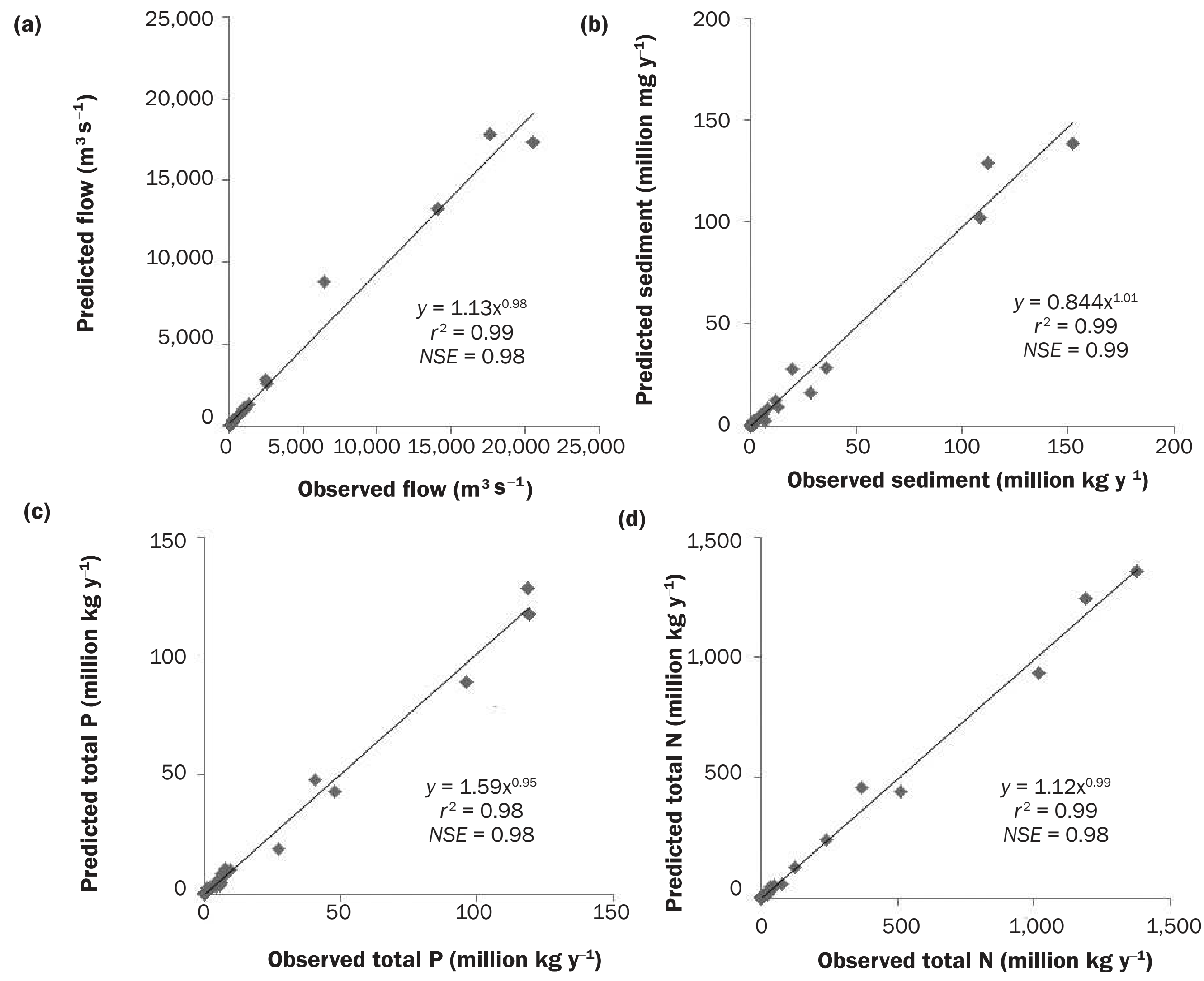
CEAP predictions were also compared to SPARROW predictions at each HUC8 outlet. Figure 5 contains Cropland CEAP and SPARROW nutrient predictions as scatter plots in both log and real domains. Comparisons in real space are highly correlated ($r^2 > 0.95$) with slopes near unity. These regressions are highly influenced by HUC8s along the Mississippi River, which have large loads; CEAP modeling framework and SPARROW predictions are well correlated in this region. Comparisons in log space show less variability at greater loads, which would be expected as under-predictions and over-predictions at eight-digit HUCs cancel out with an ever increasing number of contributing HUCs. Large errors are apparent with a few individual HUCs; however, upon investigation these are primarily the result of a discrepancy in reservoir placement or existence within individual HUC8s between CEAP and SPARROW. The CEAP modeling framework uses a fixed set of reservoirs, even though new reservoirs have been constructed during the simulation period (1960 to 2006). The decision to include or exclude individual structures likely differed between the two modeling efforts. These discrepancies in a relatively small number of HUC8s are difficult to avoid. Overall, the good agreement between predictions from the CEAP modeling framework and the SPARROW model, which are dramatically different modeling tools, lends credibility to both frameworks.

Nutrient Delivery to Local Waters. The CEAP modeling framework was used to predict the contribution of N and P from the landscape to local waters (water bodies that drain area ≤4,000 km^2 (≤1,500 mi^2) approximately). Point source contributions of nutrients were not considered in these landscape source predictions, but they are included in total loading predictions. Nutrient delivery ratios were calculated by both APEX and SWAT to represent the HUC8 level subbasin size in CEAP. Edge-of-field loads to first order streams would likely be somewhat greater than those shown in figure 6 at the HUC8 level. Nutrient losses to local waters were strongly correlated with the fraction of cultivated land use, density of tile drains, and precipitation as identified through multiple linear regressions using Minitab (Minitab 2010). Collectively these factors explain 67% of the variability in total N loads. The highest nutrient loads on a per acre basis occur in the upper and lower portions of the MRB. Nutrient losses from the western portion of the MRB are lower, primarily due to less intensive agriculture and reduced runoff (figure 3). The distributions of nutrient yields to local waters are visually similar to those predicted by the SPARROW model for the same region as presented by Robertson et al. (2009).

Sediment and nutrient loss to local waters are given for the entire MRB by source for both point sources and selected land uses (figure 7) and by aggregated source for each region (figure 8). The MRB is comprised of 10% cultivated cropland, 49% grassland, 29% forests, 7% urban, and 6% other land uses mainly wetlands and water. Overall, cultivated cropland was predicted to be the dominant source of sediment (59%), N (58%), and P (46%) delivery to local waters, but this was not true for each region (figure 8). These estimates agree relatively well with SPARROW cropland predictions for N (66%) and P (43%) (Alexander et al. 2008). In contrast, CEAP modeling framework sim-

Figure 4

Conservation Effects Assessment Project modeling framework calibration predictions vs. (a) estimated flow, (b) sediment, (c) total phosphorus (P), and (d) total nitrogen (N) from selected US Geological Survey stream gages. Average annual values (1960 to 2006) at each site are compared.



ulations predicted that grassland including hayland and rangeland was responsible for 22% of N and 15% of P load to local waters, whereas SPARROW predicted grassland contributions of 5% for N and 37% for P (Alexander et al. 2008). The reasons for differences in grassland predictions are not known.

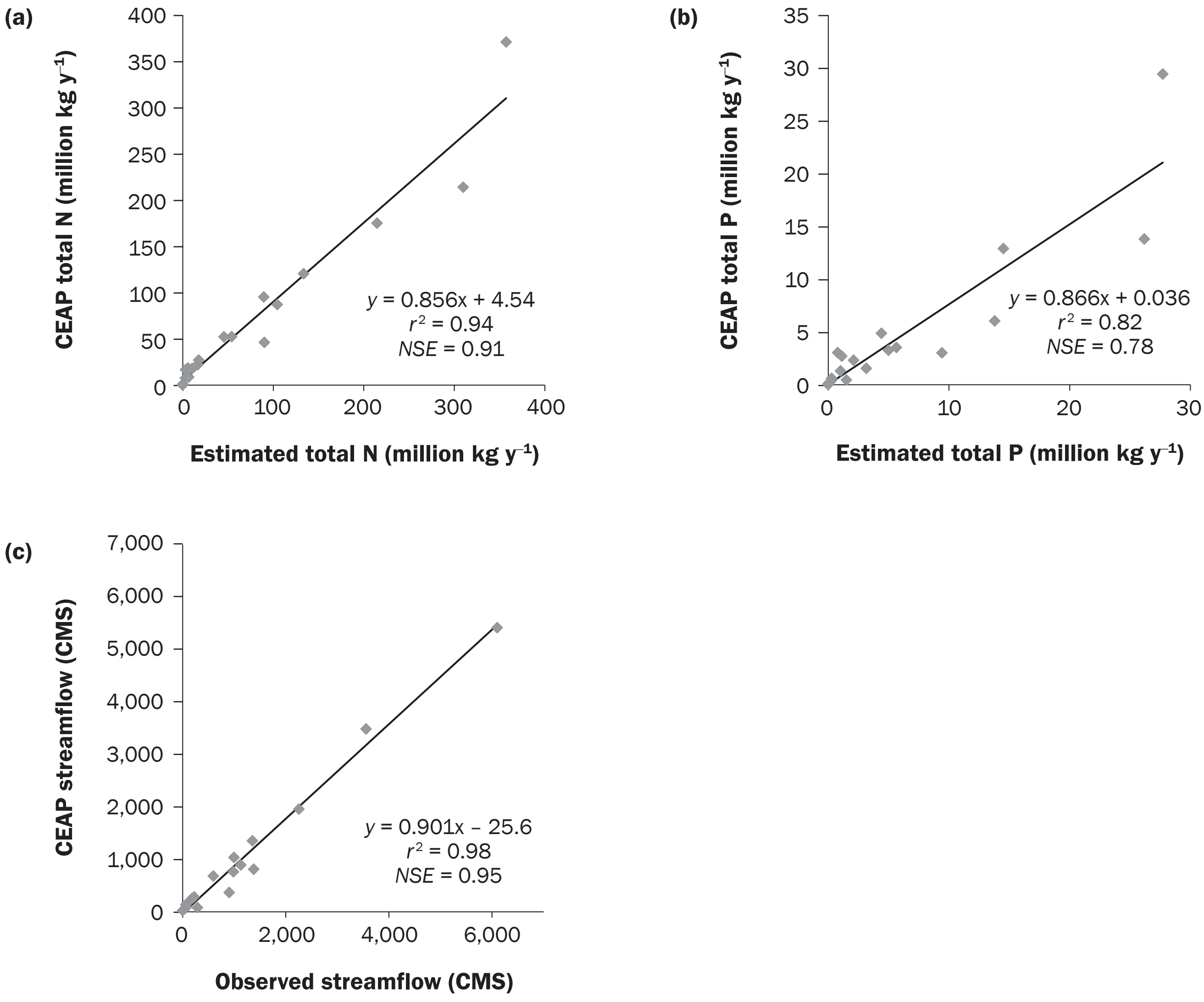
Point source contributions predicted by the Cropland CEAP modeling framework are greater for P (18%) than N (8%) (figure 7). These predictions are lower than those of USEPA (2007) (22% N and 34% P); however, USEPA (2007) estimates do not consider in-stream losses, whereas CEAP modeling framework predictions account for in-stream losses from the point of discharge to the HUC8 outlet when considering local waters. In the Tennessee and Arkansas/Red River basins, P point source load predictions exceed those from cultivated cropland. Nitrogen load predictions from point sources are typically smaller than from cultivated cropland.

Urban nonpoint sources, which include all partially impervious land uses including construction sites, roads, and bar ditches, were predicted by the CEAP modeling framework to be significant sources of N (5%) and P (10%) in the MRB. These urban predictions are not directly comparable to SPARROW which combined both urban and point sources (9% N and 12% P). Combined urban and point sources as predicted by the CEAP modeling framework were greater (13% N and 28% P).

Delivery to the Gulf of Mexico. Whereas estimated nutrient delivery from sources to local waters may be used to infer the relative contributions of sources at the local level, these are not appropriate to estimate loads delivered to the Gulf. CEAP modeling framework simulations predicted that 120 million t (135 million tn) of sediment were generated in the uplands and that another 46 million t (51 million tn) were generated through channel degradation each year in the MRB. The simulations also predicted that 58% of the N and 54% of the P entering streams from all sources was ultimately delivered to the

Figure 5

Conservation Effects Assessment Project (CEAP) modeling framework validation. CEAP predictions vs. (a) nitrogen (N), (b) phosphorus (P), and (c) estimated flow from selected US Geological Survey stream gages. Average annual values (1970 to 2007) at each site are compared. CEAP predictions of (d and e) P and (f and g) N, as compared to SPAtially Referenced Regressions On Watershed attributes (SPARROW) predictions for 848 8-digit hydrologic units in the Mississippi River Basin (note linear and log-log scales are presented).

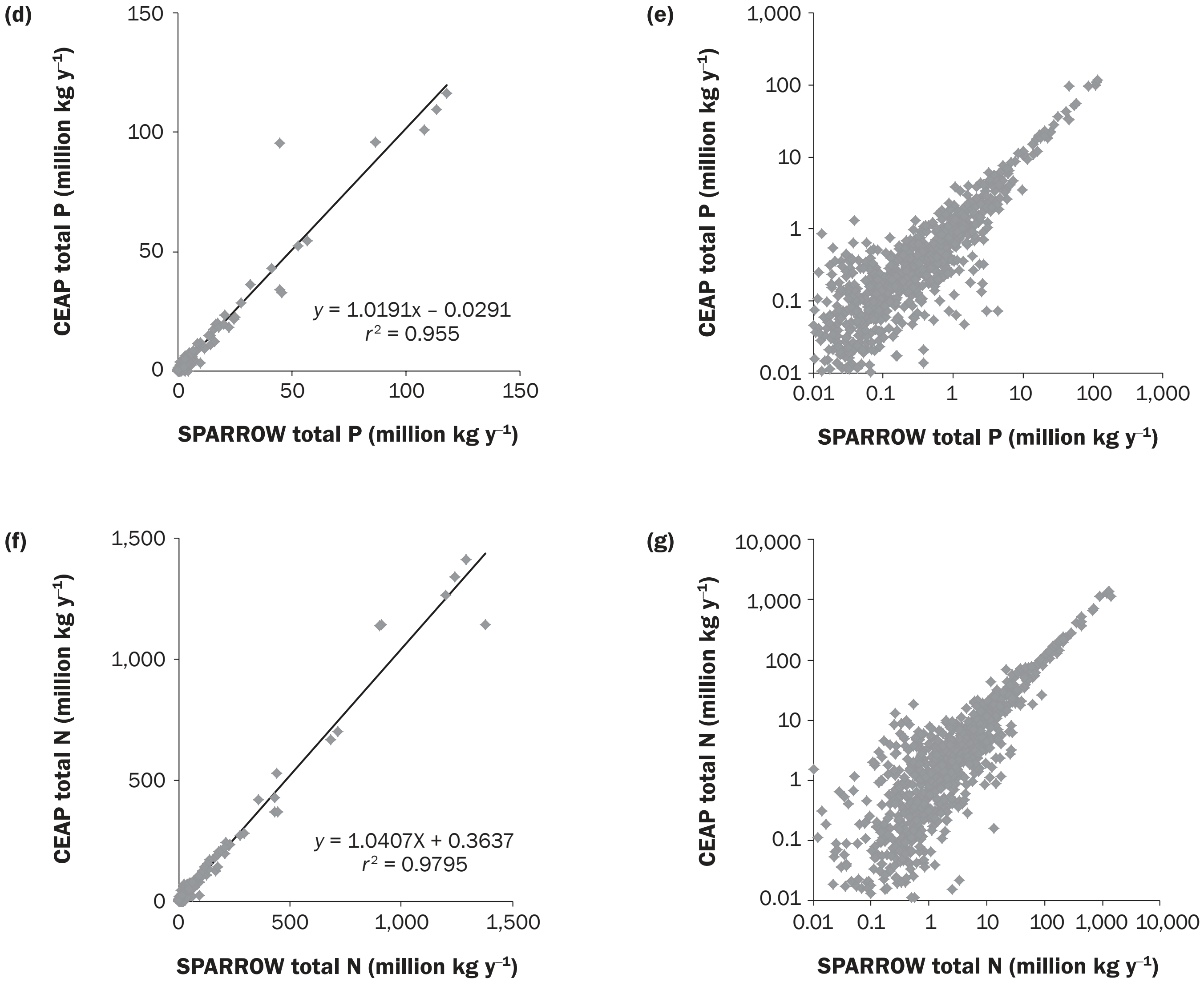


Gulf with the remainder being sequestered or lost in lakes, reservoirs, rivers, and streams. The delivery ratio, shown in figure 9 is the fraction of the in-stream load in local waters (HUC8 outlet) ultimately delivered to the Gulf. These data illustrate the variability in delivery from differing portions of the MRB. In general, sources further upstream deliver smaller nutrient loads to the Gulf. Reservoirs appear to be especially effective in reducing delivery from large portion of the Tennessee, Missouri, Red, and Arkansas River regions. Delivery along the main stem of the Mississippi is relatively high with 87% of N and 90% of P at the confluence of the Missouri and Mississippi Rivers reaching the Gulf. This finding is supported by Robertson et al. (2009), who predicted similar nutrient delivery (89% of N and 88% of P) at the same location.

The high delivery region near the main stem of the Mississippi River (figure 9) also coincides with areas with elevated nutrient yields to local waters. The per unit area load that contributes to the Gulf (figure 10) is the product of the data in figures 7 and 10. This combination of high delivery to local waters and high in-stream delivery tends to increase the relative contribution to the Gulf from this agriculturally intensive region, particularly for N. The contributions of individual sources to the Gulf and the load fraction from each region are shown in figure 11. The relative contribution nutrient load from cultivated agriculture to local waters and to the Gulf is similar, differing by less than 1%.

Figure 5 continued

Conservation Effects Assessment Project (CEAP) modeling framework validation. CEAP predictions vs. (a) nitrogen (N), (b) phosphorus (P), and (c) estimated flow from selected US Geological Survey stream gages. Average annual values (1970 to 2007) at each site are compared. CEAP predictions of (d and e) P and (f and g) N, as compared to SPAtially Referenced Regressions On Watershed attributes (SPARROW) predictions for 848 8-digit hydrologic units in the Mississippi River Basin (note linear and log-log scales are presented).



Where the highest loads originate, however, is altered by the inclusion of the delivery factor. The worst 10% of cultivated lands contribute 24% of the entire N load from all cultivated agriculture to local waters. If delivery to the Gulf is considered, the worst 10% (not necessarily the same HUC8s) contribute 33% of the entire cultivated N load to the Gulf. This implies that targeted conservation efforts should consider delivery to the Gulf for optimal impact. The importance of delivery in targeting conservation efforts by area is apparent (figure 9). Large portions of the western regions in the MRB contribute less than 10% of their nutrient load to the Gulf. Conservation efforts in these areas are unlikely to significantly impact loads to the Gulf, though they may be beneficial to local waters (figure 6). The Upper Mississippi, Lower Mississippi, and Ohio basins contribute the largest amount of nutrients delivered to the Gulf. Conservation efforts in these areas should yield the greatest Gulf impact. These findings are similar to those by Robertson et al. (2009), which found the highest delivered yields originated in watersheds in the Central Mississippi, Ohio, and Lower Mississippi River basins.

Effectiveness of Conservation Practices and Policy. The primary objective of the Cropland CEAP effort is to evaluate the effectiveness of conservation practices and policy in the United States. The CEAP

Figure 6

Conservation Effects Assessment Project modeling framework predicted (a) nitrogen and (b) phosphorus delivery to local waters at the hydrologic unit (HUC8) scale.

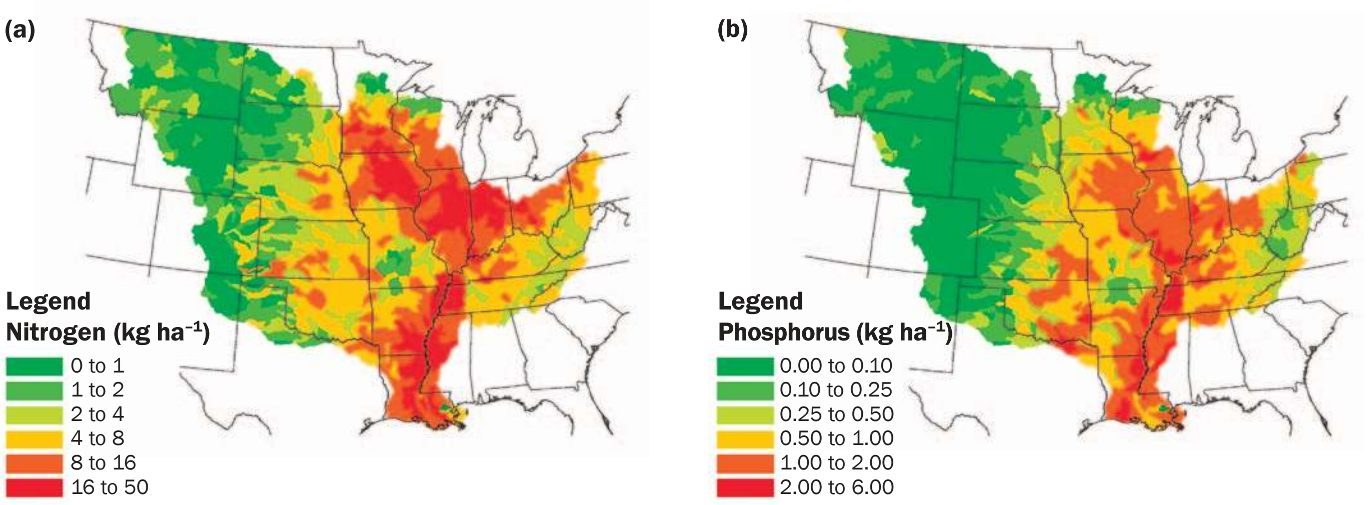


Figure 7

(a) Flow, (b) sediment, (c) total nitrogen, and (d) total phosphorus loads delivered to local waters by source as predicted by the Conservation Effects Assessment Project modeling framework.

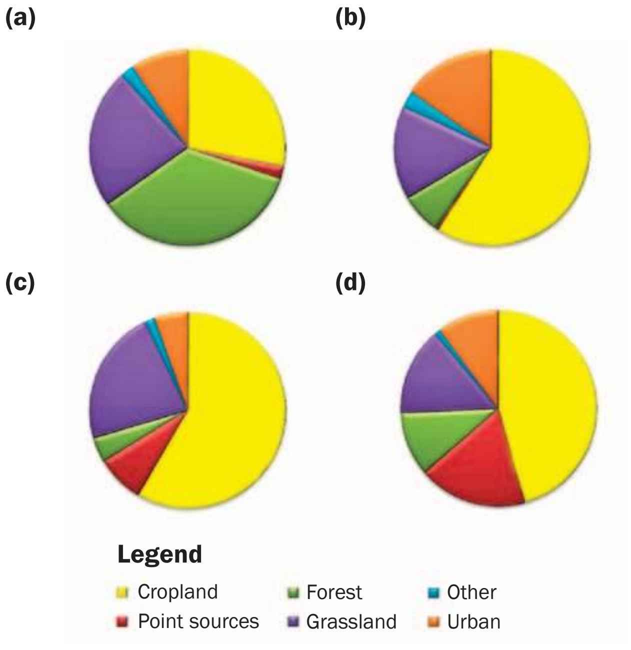


Figure 8

Sources of (a) sediment, (b) total nitrogen, and (c) total phosphorus delivery to local waters as predicted by the Conservation Effects Assessment Project modeling framework.

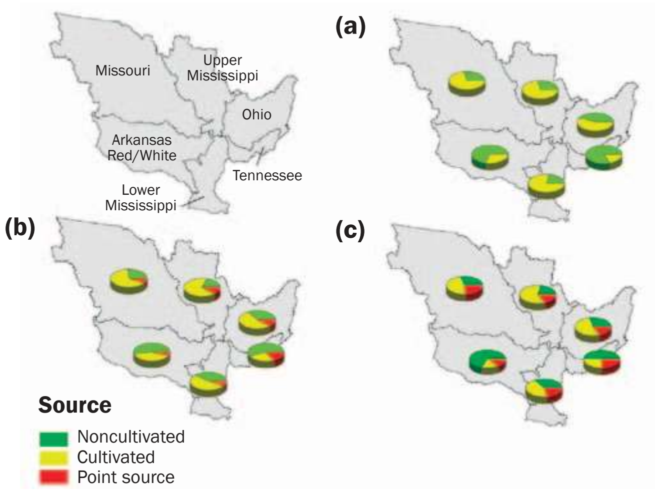


Figure 9
In-stream (a) nitrogen and (b) phosphorus delivery to the Gulf of Mexico as predicted by the Conservation Effects Assessment Project modeling framework (excludes delivery from edge-of-field to hydrologic unit [HUC8] outlet).

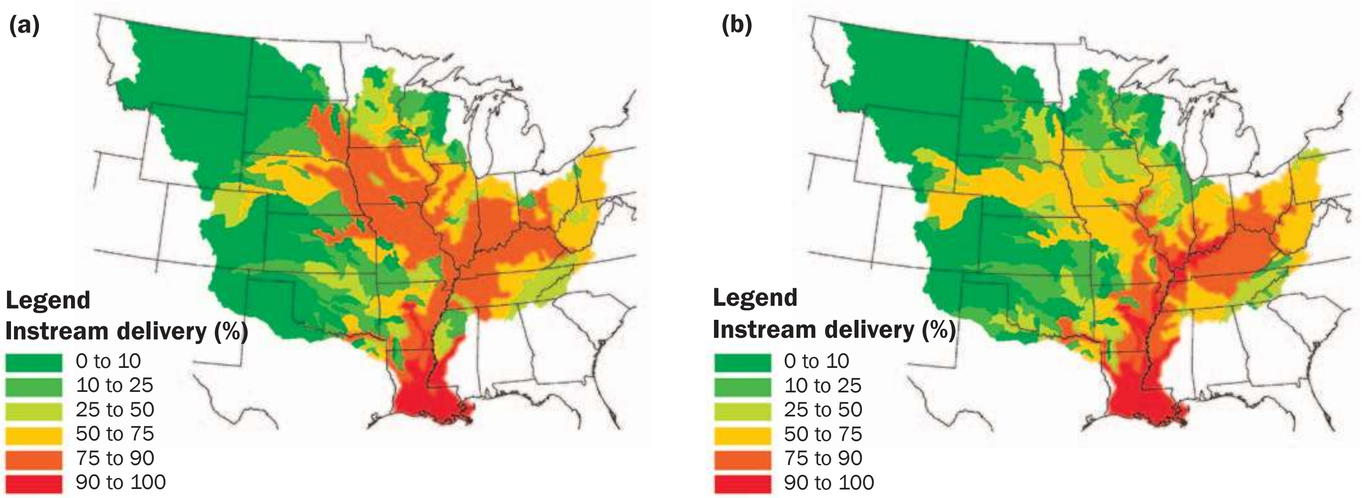
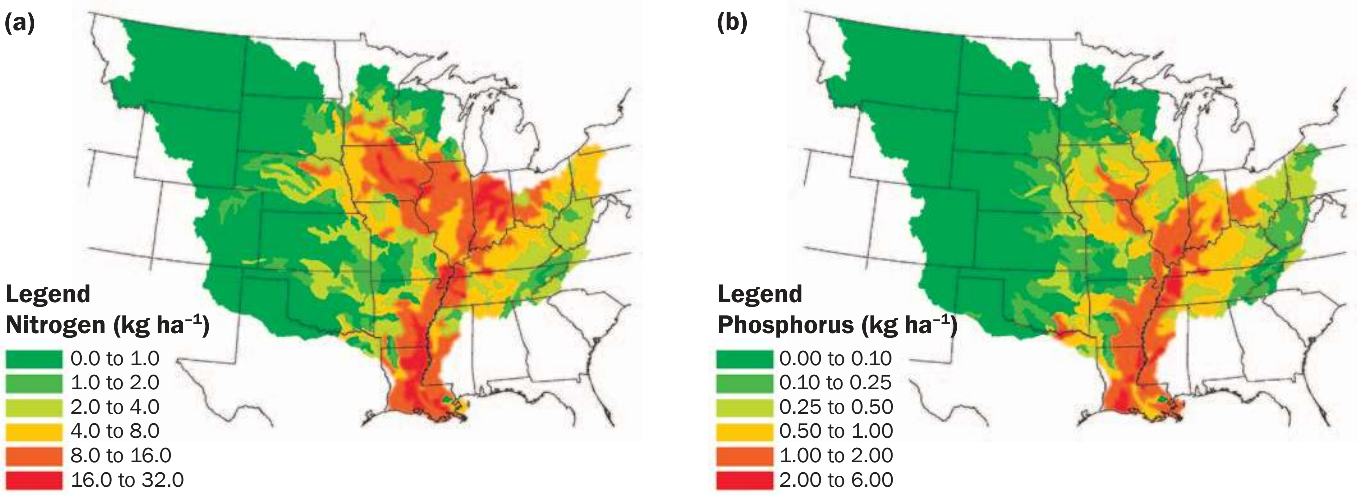


Figure 10
(a) Nitrogen and (b) phosphorus yields from the landscape (all land uses) delivered to the Gulf of Mexico as predicted by the Conservation Effects Assessment Project modeling framework.



modeling framework contains a variety of structural and cultural conservation practices including terraces, contour farming, buffer strips, waterways, reduced tillage, nutrient management, cover crops, and crop rotation. A comprehensive list of practices in available in Santhi et al. (2012). The CEAP modeling framework predicted that the current level of cropland conservation reduced the total amount of N and P delivered to the Gulf from all sources by 18% and 20%, respectively (table 2).

The effect of conservation policy is perhaps better realized by isolating the effect that conservation practices have had on the nutrient load from cultivated agriculture alone which is delivered to the Gulf. The contribution from cultivated agriculture to the Gulf was predicted to be reduced by 28% for N and 45% for P (table 2) due to the current level of conservation. The reason that P loss reductions were larger is likely attributable to the differing principle transport mechanisms between N and P. Conservation practices designed to reduce erosion will also reduce the transport of particulate P attached to the eroded soil; however, the same practices may have little effect on soluble N losses. Practices designed to control erosion through reduced tillage may reduce particulate nutrient losses while increasing soluble losses. This phenomenon is reflected in the land use/tillage nutrient export coefficients derived from measured data (Harmel et al. 2006).

The benefits of conservation practices on loads to the Gulf vary significantly across the

Figure 11

(a and c) Nitrogen and (b and d) phosphorus delivered to the Gulf of Mexico by (a and b) source and (c and d) regional contribution from cultivated agriculture alone as predicted by the Conservation Effects Assessment Project modeling framework.

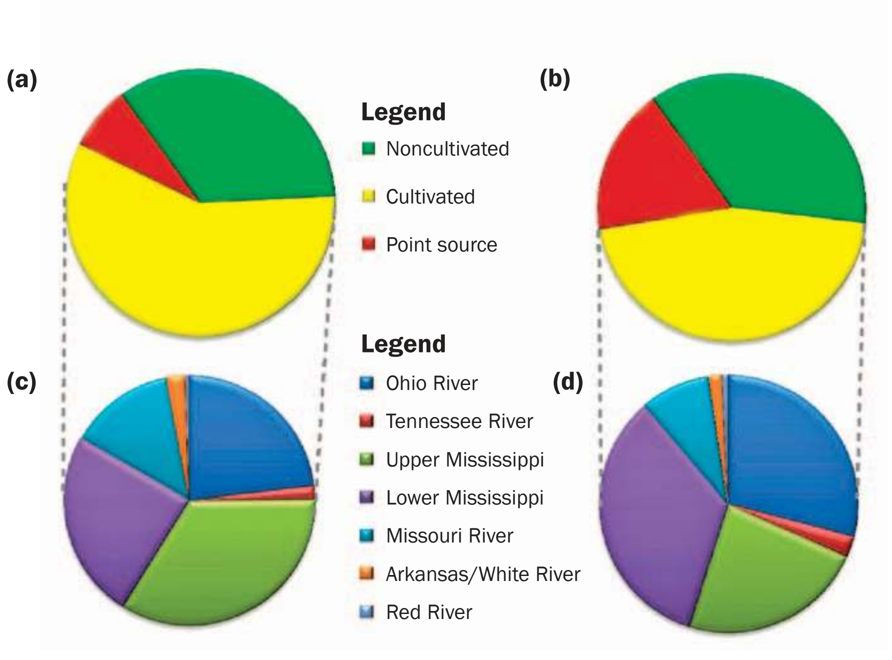


Table 2

Effects of established conservation practices on nutrient loads to the Gulf of Mexico via the Mississippi River system as predicted by the Conservation Effects Assessment Project modeling framework.

Scenario	Total nitrogen (million kg y^{-1})	Total phosphorus (million kg y^{-1})
Load from all sources delivered to the Gulf		
No conservation practices	1,640	165
Current conservation condition	1,350	132
Reduction due to conservation	18%	20%
Load from only cultivated agriculture delivered to the Gulf		
No conservation practices	1,110	115
Current conservation condition	796	63
Reduction due to conservation	28%	45%

basin (figure 12). Practices in regions such as the upper Missouri and western Arkansas/Red with relatively low nutrient delivery (figure 9) are less effective. Even without conservation, nutrients from these areas are trapped in reservoirs before reaching the Gulf. The Tennessee region had a smaller cultivated agriculture contribution in general (figure 8), coupled with relatively low (25% to 50%) delivery; therefore, conservation practices here were less effective than in other areas. Areas with relatively high nutrient delivery (>80%) and extensive agricultural production, such as the lower Missouri, upper and lower Mississippi, and Ohio, show the most benefit from the establishment of conservation practices.

Summary and Conclusions

The CEAP modeling framework and its application in a comprehensive evaluation of nutrient sources and delivery to the Gulf is presented in this manuscript. The CEAP modeling framework is the product of a multiagency team utilizing the most suitable data and simulation technology. The CEAP modeling framework developed for the MRB was calibrated for flow, sediment, N, and P and then validated using multiple approaches. Calibration and validation procedures were sufficient to provide a science-based tool for evaluating pollutant sources and delivery and predicting the effect of agricultural conservation practices.

Simulation results indicate that cultivated agriculture was the largest source of nutrients on average to both local waters and the Gulf, but that other sources were dominant in individual regions in the MRB. In addition, point sources contributed substantial loading of P to the Gulf, which is important as primary algal production is often limited by P during the spring in the near shore northern Gulf. Predicted nutrient loads to local waters indicated that the Upper Mississippi, Ohio, and Lower Mississippi regions were the highest relative contributors, presumably due to the amount of cultivated agriculture and ample precipitation. These regions also had relatively high nutrient delivery (>70%), further increasing their relative contribution to the Gulf. In addition, the very high nutrient delivery areas near the main stem of the Mississippi River, from which 87% of N and 90% of P were predicted to reach the Gulf, also coincided with elevated nutrient yields to local waters. These results indicate the importance of targeted conservation practice implementation and consideration of local water and/or Gulf impacts depending on program goals. We predict that establishment of conservation practices on cultivated lands (as reported by the CEAP survey) in the MRB have reduced nutrient loads to the Gulf by approximately 20%. The nutrient load contribution predicted from cultivated agriculture alone has been reduced by a significantly larger margin (28% to 45%).

As state and federal conservation programs administered by or funded through the USDA and USEPA are subject to increasing pressure to prove their effectiveness, programs will increasingly rely on simulation tools such as the CEAP modeling framework. These same tools can also guide conservation policy and implementation to provide the most environmental benefit per US dollar spent.

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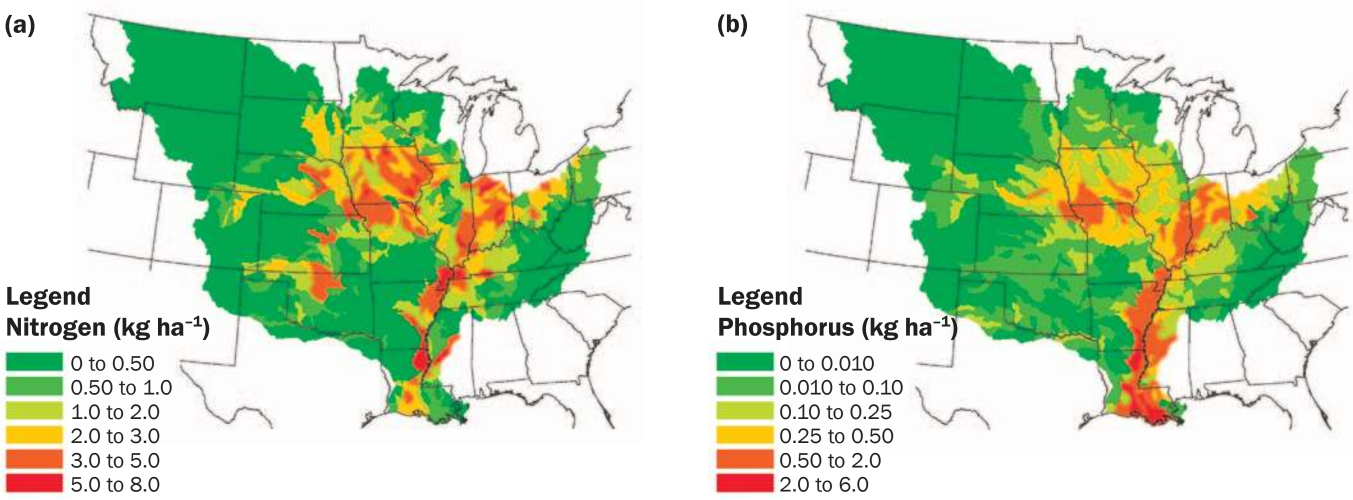
Figure 12

Reduction in (a) nitrogen and (b) phosphorus loads to the Gulf due to current conservation practices on cultivated land (expressed as load per unit HUC8 area) as predicted by the Conservation Effects Assessment Project modeling framework.



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