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SPARROW Models Used to Understand Nutrient Sources in the Mississippi/Atchafalaya River Basin

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Nitrogen (N) and phosphorus (P) loading from the Mississippi/Atchafalaya River Basin (MARB) has been linked to hypoxia in the Gulf of Mexico. To describe where and from what sources those loads originate, SPAtially Referenced Regression On Watershed attributes (SPARROW) models were constructed for the MARB using geospatial datasets for 2002, including inputs from wastewater treatment plants (WWTPs), and calibration sites throughout the MARB. Previous studies found that highest N and P yields were from the north-central part of the MARB (Corn Belt). Based on the MARB SPARROW models, highest N yields were still from the Corn Belt but centered over Iowa and Indiana, and highest P yields were widely distributed throughout the center of the MARB. Similar to that found in other studies, agricultural inputs were found to be the largest N and P sources throughout most of the MARB: farm fertilizers were the largest N source, whereas farm fertilizers, manure, and urban inputs were dominant P sources. The MARB models enable individual N and P sources to be defined at scales ranging from SPARROW catchments (~50 km^2) to the entire area of the MARB. Inputs of P from WWTPs and urban areas were more important than found in most other studies. Information from this study will help to reduce nutrient loading from the MARB by providing managers with a description of where each of the sources of N and P are most important, thus providing a basis for prioritizing management actions and ultimately reducing the extent of Gulf hypoxia.

Nutrients (primarily nitrogen, N, and phosphorus, P) directly input into streams or exported from agricultural and urban areas can lead to local problems, such as the overabundance of benthic algae, phytoplankton, and macrophytes, and downstream problems, such as eutrophication of lakes, estuaries, and bays. Excess N and P exported from local drainages located throughout the entire Mississippi/Atchafalaya River Basin (MARB) have been linked to hypoxia in the Gulf of Mexico (USEPA, 2000). The Gulf of Mexico hypoxic zone (the area with bottom water having dissolved oxygen concentrations <2 mg/L) is the second-largest human-caused zone of hypoxia in the world's coastal waters (Scavia and Evans, 2012). Hypoxia in the Gulf was originally thought to be driven by excessive N loading (primarily nitrate); however, recent studies found that P limitation is also occurring in near-shore regions because the excessive N loading has dramatically altered N:P ratios (USEPA, 2007). The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2008) established the goal of reducing the 5-yr moving average areal extent of the Gulf of Mexico hypoxic zone to <5000 km^2. To achieve that goal, the USEPA Science Advisory Board found that a dual strategy is needed that achieves at least a 45% reduction in both N and P loading from the MARB from the average annual 1980–1996 fluxes (USEPA, 2007).

Reducing nutrient inputs from all sources is a comprehensive way to achieve these goals; however, understanding which N and P sources are most important in specific areas and taking actions to reduce inputs from these sources would be more efficient. A few studies have described the distribution in N and P loading throughout the MARB and their major sources, and how the relative importance of these sources vary between N and P. Goolsby et al. (1999) related average annual N and P yields from 42 large basins from 1980 to 1996 to inputs from point sources, fertilizers, manure, legume crops, and other factors represented by runoff (atmospheric deposition, groundwater, and soil erosion) to describe yields from large river basins throughout the MARB by developing yield regression relations that were a function of these sources. They concluded that farm fertilizers and atmospheric deposition were the main N sources and that

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Abbreviations: APEX, Agricultural Policy/Environmental eXtender; DSS, decision support system; DVF, delivery variation factor; MARB, Mississippi/Atchafalaya River Basin; MRB, major river basin; NLLSR, nonlinear least squares regression; NWIS, National Water Information System; PCS, Permit Compliance System; RB, river basin; RF1, Reach file version 1.0; SAB, Science Advisory Board–Hypoxia Advisory Panel; SPARROW, Spatially Referenced Regression On Watershed attributes; SWAT, Soil and Water Assessment Tool; WWTPs, wastewater treatment plants.

farm fertilizers and other inputs represented by runoff were the main P sources.

David et al. (2010) and Jacobson et al. (2011) also used multiple-regression techniques relating nitrate and P yields from monitored sites in the MARB with various inputs and environmental characteristics to estimate N and P yields from each county in the MARB and determine which input and land-use variables were most important. David et al. (2010) concluded that fertilized corn in tile-drained watersheds was the dominant source of nitrate to the Gulf, wastewater treatment plants (WWTPs) effluent had localized effects, and atmospheric deposition and manure were not significant explanatory variables for N. Jacobson et al. (2011) concluded that the area of cropland, fertilizer inputs, and P consumed by humans were the dominant P sources and that manure was not a significant contributor of P.

Regression approaches, such as the multivariate equations developed in these studies to predict various water-quality characteristics from statistically significant whole-basin characteristics, may be good for describing the distribution in concentrations, loads, and yields; however, the simple regression approach has several weaknesses. A principal weakness of the regression approach is that it does not explicitly describe where the long-term storage/removal (e.g., through denitrification) of nutrients occurs during transport and does not separate the processes that occur on the land and in the streams, which complicates identifying and tracking the sources that contribute to the total load reaching downstream waters. In addition, results from simple regression analyses can be very misleading when trying to obtain cause-and-effect relations because individual or combinations of individual source variables may act as surrogates for other sources (Box, 1966).

SPAtially Referenced Regression On Watershed attributes, or SPARROW, watershed models, developed by the USGS, have also been used to estimate N and P yields throughout the MARB and quantify the importance of various nutrient sources (Smith et al., 1997). SPARROW models describe the sources, transport, and fate of nutrients in watersheds. Smith et al. (1997) developed national-scale SPARROW models with nutrient inputs similar to 1987 to describe the relative importance of point sources, farm fertilizers, manure, atmospheric deposition, and nonagricultural land. Alexander et al. (2008) also developed national-scale SPARROW models but used inputs similar to 1992 and 2002 to describe the relative importance of various crops, urban and population sources, land uses, and atmospheric deposition. These studies found that agricultural inputs were the largest N source, whereas manure (especially nonrecoverable manure on pasture and rangeland) was the largest P source. These national-scale models were calibrated using 381 to 425 relatively large basin sites and either had limited point-source information (1987 model) or used population in each catchment as a surrogate for point-source input (1992 and 2002 models).

Recently, the USGS developed detailed regional-scale SPARROW models for several major river basins (MRBs) in the United States (Preston et al., 2011) using national geospatial datasets based on land-use conditions and N and P inputs similar to 2002 (Maupin and Ivahnenko, 2011; Wieczorek and Lamotte, 2011), and estimated long-term average N and P loads detrended to 2002 (discussed later) from nearly 3000 sites (Saad et al., 2011). Parts of four MRBs are included in the MARB: Robertson and Saad (2011)—Upper Midwest, including the Upper and Middle Mississippi and Ohio River Basins; Brown et al. (2011)—Missouri River Basin; Rebich et al. (2011)—Lower Mississippi, Arkansas, and Red/Ouachita River Basins and Texas Gulf Basin; and Hoos and McMahon (2009) and García et al. (2011)—southeastern United States, including the Tennessee River Basin. These models were used to describe the distributions in N and P yields in their respective areas, as well as the relative importance of individual N and P sources; however, none of these models covered the entire MARB. Preston et al. (2011) summarized the results from these regional SPARROW models and noted that throughout most of the MARB, fertilizers applied to croplands were the dominant N source, whereas manure and fertilizers applied to croplands were the dominant P sources.

The USDA Conservation Effects Assessment Project (CEAP) recently completed an evaluation of the sources and delivery of N and P from throughout the MARB using the Agricultural Policy/Environmental eXtender (APEX) and Soil and Water Assessment Tool (SWAT) models (White et al., 2013). Both APEX and SWAT are highly parameterized hydrologic and water-quality models that operate on a daily time step and consist of process-based routines that simulate major hydrologic, sediment, and nutrient-fate processes. In these models, N and P sources were partitioned into inputs from cropland, grassland, point sources, urban nonpoint sources, forested areas, and other sources. The models were calibrated using data from 38 relatively large sites with detailed flow and water quality information from 1960 to 2006, and used municipal and industrial point sources estimated for 1977 to 1981 by Alexander (1998). Simulation results indicated that cultivated cropland was the dominant source of both N and P for the entire MARB, but the relative importance of sources varied among regions, and that point sources accounted for 8% of the N and 18% of the P delivered to the Gulf.

The USEPA Science Advisory Board Hypoxia Advisory Panel examined the literature and concluded that agriculture was the largest source of N and P; manure was a more significant source for P than N; and where N fluxes were greatest, inputs from manure tend to be less important (USEPA, 2007). They also concluded that point source contributions were more important than previously estimated in most studies, and may represent 22 and 34% of the average annual N and P flux, respectively (USEPA, 2007; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). These proportions were based on the assumption that 100% of point sources were exported to the Gulf.

All of these studies found relatively similar results—that areas of the central Corn Belt had highest yields and areas in the western part of the MARB had lowest yields, agricultural activity was the largest source of N and P delivered from the MARB, and urban inputs can have highly significant local effects. The predictions of the source shares that are needed for management, however, varied widely. The studies cited above concluded that fertilizers accounted for between 50 and 67% of the N input to the Gulf and 31 to 37% of the P, and that manure ranged from being insignificant to 15% of the N and from being insignificant to 40% of the P. The relative importance of point sources varied from 7 to 22% for N and from 10 to 34% for P. Therefore, there is a need to refine the knowledge of the origin and major sources of N and P reaching the Gulf of Mexico.

In this article, we describe N and P SPARROW models developed explicitly for the MARB. The MARB models were developed on the basis of information assembled for the various regional-scale N and P SPARROW models (Preston et al., 2011). The MARB models were developed using national geospatial datasets with N and P inputs similar to 2002 (including input from WWTPs rather than using population as a surrogate) and long-term detrended loads from 856 sites for N and 988 for P, including many more sites on small streams than used in previous national-scale models. The MARB SPARROW models are used (i) to estimate N and P loads and yields from throughout the MARB; (ii) to describe the geographic origins of N and P reaching the Gulf of Mexico; (iii) to describe the relative importance of each N and P source for each catchment and main river basin; and (iv) to compare MARB SPARROW model source allocations with allocations from previous studies.

Materials and Methods

Study Area

The MARB drains about 3,200,000 km^2 or about 41% of the conterminous United States, and it has a wide range of land uses and hydrologic conditions (USGS, 2000). The MARB has some of the most productive farming regions in the world, including the intensive agricultural region of the midwestern United States referred to as the Corn Belt (Gage, 1996), large forested areas, and many large cities (e.g., Chicago, IL, and St. Louis, MO). Goolsby et al. (1999) partitioned the MARB into nine main river basins (RBs); the land uses of each area are given in Table 1. Runoff throughout the MARB ranges from less than 5 cm/yr in the arid west to more than 60 cm/yr in the east.

SPARROW Model

SPARROW is a spatially explicit watershed model that uses a mass-balance approach to estimate nutrient sources, and nonconservative transport and transformation (i.e., losses) of nutrients throughout watersheds under long-term steady-state conditions (Smith et al., 1997; Schwarz et al., 2006; Alexander et al., 2008). A brief overview of the SPARROW model is given here and a detailed description is given in the Supplemental Material to this article. Given a specification of nutrient sources, the model estimates a delivery variation factor (DVF) for each catchment that is a function of various "land-to-water delivery" factors. The land-to-water delivery factors that define the DVF are statistically significant landscape properties, such as climate, soils, and artificial drainage. Part of the nutrient flux is attenuated or decayed, via losses in streams or reservoirs, as the nutrients travel down the stream network (Alexander et al., 2008).

During model development, a variety of model specifications are evaluated to determine which sources and landscape characteristics, among those that can be reasonably represented for the study area, are important in controlling N and P transport. Model specifications are based on knowledge of the major nutrient sources, factors known to affect nutrient concentrations and transport, and our experience in SPARROW modeling. To ensure proper model specification, the range of nutrient sources and landscape characteristics that occurs in the entire study area should be represented by the monitored watersheds (calibration sites). Sources and factors affecting transport that are not well represented in the monitored watersheds may not be included in the models. Sources identified as statistically significant (typically $p < 0.05$) in explaining the distribution in N and P loads are retained, or, if statistically insignificant, they are combined with other sources in a series of model runs until an acceptable specification is obtained, in terms of model fit (RMSE, R^2 values, model-estimated coefficients, variance inflation factors, and residual plots). Parameter coefficients for the sources, land-to-water delivery factors, and instream- and reservoir-loss terms are statistically estimated by using nonlinear least squares regression (NLLSR; Schwarz et al., 2006), based on calibrations with long-term mean annual loads normalized to a specific base year (described below) from sites throughout a study area. Because of SPARROW's

Table 1. Land use characteristics (USGS, 2000) of and nitrogen and phosphorus inputs (2002) into each main river basin in the Mississippi/Atchafalaya River Basin.

River basin	Area	Land use				Nutrient input						
		Urban	Agriculture	Pasture/ grassland	Forest/ wetland	WWTPs† N	WWTPs P	Farm fertilizers N	Farm fertilizers P	Confined manure N	Total manure P	Atmospheric N
	km^2	%				kg/km^2/yr						
Upper Ohio	249,000	10.1	12.7	17.2	59.0	156.95	10.77	1299	252	280	151	1378
Lower Ohio	279,000	8.3	25.5	17.9	46.4	82.34	9.57	2413	496	462	236	1231
Upper Missouri	817,000	2.8	21.0	51.5	23.1	5.99	0.78	1107	191	173	155	348
Lower Missouri	512,000	4.7	31.9	43.5	18.9	28.42	3.11	2688	387	510	241	692
Upper Mississippi	222,000	6.1	35.8	14.4	39.5	49.08	7.80	2482	431	972	152	958
Middle Mississippi	275,000	10.1	56.9	14.0	17.5	210.73	16.09	4853	874	795	197	1169
Arkansas	411,000	4.6	21.3	50.5	22.4	22.07	2.58	1506	193	568	236	701
Lower Mississippi	186,000	5.9	31.0	12.7	47.6	40.82	5.25	2626	404	277	146	1079
Red/ Ouachita	241,000	5.1	16.4	27.1	49.5	16.51	1.31	1186	138	471	251	841
Total	3,197,000	5.6	26.9	34.4	31.4	54.46	5.10	2051	337	448	196	800

† WWTPs, wastewater treatment plants.

mass-balance structure, if actual sources are not represented in the model (perhaps because of lack of data to document them), then mass from these non-included sources (which are reflected in measured loads) will be represented by other sources that are at least partially correlated with the missing sources or reflected in model error. To demonstrate the robustness of the final models, mean coefficient values and confidence intervals are determined using a nonparametric bootstrap procedure (Schwarz et al., 2006; Robertson et al., 2009).

SPARROW's mean annual predictions of nutrient mass for stream reaches include the load, yield, volumetrically weighted concentration, and source-share contributions (percentage of the load for each source). Loads and yields reaching the end of each catchment and from the total drainage area upstream at any location are estimated. In addition, the incremental and total loads or yields and source-share contribution from any location are described as that part ultimately transported (delivered) downstream to a specific location, in this case the Gulf of Mexico, after accounting for the downstream removal/attenuation in streams and reservoirs.

Data Used to Calibrate the SPARROW Models

Four types of data are used to "develop" or calibrate SPARROW models: a stream network defining reaches and catchments, N and P loading data for many sites in the study area, inputs from all important sources of the constituent being modeled, and information describing environmental factors that may cause significant variability in the land-to-water delivery of nutrients.

Stream Network Information

Flow paths were defined by streams and reservoirs in the enhanced stream-reach file 1 (RF1; 1:500,000 scale; Nolan et al., 2002), with incremental reach catchments delineated from 100-m digital elevation models (Brakebill et al., 2011). Within RF1, MARB has 27,475 reaches (catchment sizes: fifth percentile, 36.5 km^2; median, 329 km^2; and 95th percentile, 51,200 km^2); therefore, the catchments in this model are between USGS hydrologic unit code HUC10 and HUC12 in size. The defined catchments were used to allocate all nutrient source, landscape, and aquatic characteristics to each reach (USGS, SPARROW Model Variables for Modified RF1 Catchments, accessed March 2008–August 2010 at http://water.usgs.gov/nawqa/modeling/rf1attributes.html; unless otherwise noted all spatial data in this paper are from this source).

Stream-Load Information

Long-term mean annual N and P loads for each monitored site with sufficient data (see Saad et al. [2011] and the Supplemental Material for more collection and screening information) were computed with the rating curve/regression procedure in the Fluxmaster computer program (Schwarz et al., 2006). This procedure combines concentration data with daily flow values to provide more accurate load estimates than can be obtained using individual water-quality measurements alone (Walker, 1981). Daily flow data for the period 1971 to 2006 were retrieved primarily from the USGS National Water Information System (NWIS) database, supplemented with data from a few additional agencies. Nitrogen and P concentration data for the period 1971 to 2006 were retrieved from the USEPA STOrage and RETrieval (STORET) database, the USGS NWIS database, and data from agencies that routinely collect water-quality data and use standardized sample collection and laboratory analysis protocols.

Within Fluxmaster, regression models that related the logarithm of concentration to the logarithm of daily flow, decimal time (to compensate for trends), and day of the year (to compensate for seasonality) were fit to data from each potential load site. Each regression model was then used to estimate a long-term mean annual load, normalized to the 2002 base year (Preston et al., 2009), by first calibrating the model using data from 1971 to 2006, and then estimating detrended daily loads using detrended daily flows for the entire period (see Schwarz et al. [2006] for a complete description of the detrending process). All estimated daily loads were then adjusted for log retransformation biases using methods described by Cohn (2005) and Schwarz et al. (2006). Average detrended (to 2002) annual loads were then computed by aggregating the daily detrended loads for all years with complete records of daily flow, and averaging over all such years between 1971 and 2006. The 2002 base year was selected to coincide with the most recently available explanatory geospatial data. The average detrended loads incorporate the aggregate effect of floods, droughts, and extreme seasonality that have occurred over the period 1971 to 2006.

Additional steps were taken to ensure that load estimations used in SPARROW calibration were as accurate as possible. Sites for which the regression relation performed poorly (standard error [SE] >50%) were omitted. Stenback et al. (2011) found that the rating curve/regression procedure can result in potentially biased annual load estimates after the estimated loads in log space are transformed back into real space, even after statistical transformation bias adjustments are applied if the model is mis-specified or there is nonconstant variance in the concentration/flow relation. Therefore, for each site, the total of the loads predicted by the regression model were compared to the total of the observed loads (both computed only for days when concentrations were measured), and all sites with a ratio of the total estimated load to the total observed load >1.5 and <0.667 were omitted; these values were chosen to be consistent with the 50% SE criterion for omitting sites with poor regression models. The final sites (856 for N and 988 sites for P) used in model development had a wide range in basin sizes: fifth percentile, 167 km^2; median, 2200 km^2; and 95th percentile, 61,700 km^2. All long-term mean-annual detrended loads are summarized in the Supplemental Material.

Nutrient-Source Information

Input to SPARROW models includes data that describe all major N and P sources. Some of these datasets have been refined since earlier national-scale SPARROW models were developed (Smith et al., 1997; Alexander et al., 2008). After evaluating a variety of model specifications, using knowledge of the key sources and prior modeling efforts, the following N and P sources were found to be statistically significant: WWTPs effluent, farm fertilizers, total manure (for P) and manure only from confined animals (for N), additional agricultural inputs from legume crops (including fixation), urban and developed open lands (collectively referred to as urban areas), atmospheric deposition, forest and wetland (collectively referred to as forested areas), deeply weathered loess soils, and channel erosion and streambank slumping in large rivers. Nitrogen and P inputs to each catchment were estimated for the 2002 base year, or as close to 2002 as possible. These sources are described briefly; details are in the Supplemental Material.

Inputs from WWTPs effluent were estimated from data in the USEPA Permit Compliance System, supplemented with data obtained directly from state agencies (Maupin and Ivahnenko, 2011). Previous 2002 regional models (Preston et al., 2011) combined the inputs from commercial and industrial point sources with the inputs from WWTPs as a single source. Some of the commercial and industrial inputs were either spread on land or represented water withdrawn from the stream with elevated N and P concentrations before being used and discharged back to the stream. Therefore, their inputs and importance may have been overestimated in past modeling efforts. Commercial and industrial point sources were evaluated as a separate input variable in the calibration process for the MARB models. Total atmospheric N deposition was obtained from the Community Multiscale Air Quality (CMAQ) model (Schwede et al., 2009; Hong et al., 2011; USEPA, 2012), which may include volatilized losses from natural, agricultural, and urban sources. Fertilizer and manure inputs were based on county-level estimates made by Ruddy et al. (2006). Nutrients from livestock wastes (manure) reflect contributions from excreted wastes of confined animals, including those in concentrated animal feeding operations, and from excreted wastes of unconfined animals on farms, pastures, and rangelands. Estimated inputs of N from fixation by legumes (soybean [*Glycine max.* (L.) Merr.] and alfalfa [*Medicago sativa* L.]) were based on the product of county soybean and alfalfa production and crop-specific fixation rates (Alexander et al., 2008). General land-use related inputs were based on the area in each land type represented in the 2001 National Land Cover Data (USGS, 2000): urban areas were based on the combined areas for low-, medium-, and high-density urban and open areas, and may serve as a surrogate for various diffuse urban sources; and forested areas were based on the combined area of all forested and wetland areas. Sediment mobilized from channel erosion and streambank slumping can be a source of P (Sekely et al., 2002; Lenhart, 2008); therefore, stream length of larger streams (mean discharge >1.42 m^3/s; the specific discharge value was found in the model calibration process) was used as a source variable. Specific soils are known to have elevated nutrient concentrations. Meng et al. (2008) found high nutrient losses from soil erosion on the Loess Plateau in China; therefore, the area of deeply weathered loess soils (primarily in Mississippi and western Kentucky and Tennessee; Clawges and Price, 1999) was examined as a potential N and P source.

Environmental-Setting Information

Statistical methods similar to those used to identify nutrient sources were used to identify environmental (landscape) characteristics, from the many possible characteristics that are important in explaining variability in N and P delivery to streams and losses in streams and reservoirs, including those used in previous regional SPARROW models. Environmental-setting characteristics determined to help explain variability in the delivery of N and P to streams throughout the MARB were stream drainage density, fraction of the catchment with irrigation, fraction of the catchment underlain by tile drains, precipitation, air temperature, and soil permeability, soil erodibility, soil organic matter content, and excess overland runoff. Sources of data for each of these characteristics are described here briefly, and in detail in the Supplemental Material. Soil characteristics (permeability, erodibility, and organic matter content) were compiled from the USDA STATSGO database by using methods described by Wolock (1997). Excess overland runoff, a surrogate for runoff potential, was computed with TOPMODEL (Wolock, 2003). Tile drain and irrigation information were compiled from the 1992 and 1997 National Resource Inventory datasets (USDA, 1995, 2000). Mean air temperature and precipitation, representing the 30-yr (1971–2000) average, were obtained from the PRISM database (PRISM Climate Group, 2009). Drainage density was calculated as total stream reach length divided by catchment area.

Time of travel was used to describe removal (loss) in streams (categorized by flow as small, intermediate, and large for P and used as a continuous variable for N). Time of travel was not used as a continuous variable for P because large streams were found to be a net source of P. The inverse of hydraulic loading was used to describe removal in reservoirs (Alexander et al., 2008). During model calibration, P loads in streams at high elevations were found to be consistently underestimated. Therefore, for streams at elevations >1500 m (the specific elevation was found in the model calibration process), instream P decay was set to 0. Time of travel was estimated from stream-reach length and average velocity that was extrapolated from average annual flow during 1975 to 2007 from stations throughout the United States (D. Wolock, USGS, personal communication, 2009). Hydraulic loading in reservoirs was calculated as average flow divided by surface area of reservoirs included in the National Inventory of Dams (USACE, 2013).

Results

Calibration of SPARROW Models

The MARB SPARROW N model had six sources—farm fertilizers, manure from confined animals (referred to as confined manure), additional agricultural inputs associated with legume crops, atmospheric deposition, WWTPs, and urban area; six land-to-water delivery factors—stream drainage density, fractions of catchment with irrigation and underlain by tile drains, precipitation, air temperature, and soil organic matter content; one factor describing removal in streams that is a continuous function of the time of travel; and one factor describing removal in reservoirs (Table 2). Coefficients for all sources and factors were highly significant ($p \leq 0.05$), indicating that each is important in describing the measured loads. The coefficients were robust (small SEs compared to magnitude of the coefficient, narrow 90% confidence intervals, and mean bootstrap estimates within 5% of the NLLSR estimates, except additional agricultural inputs from legume crops at 11%). This model explained 94 and 88% of the variances in the 856 monitored loads and yields, respectively, and had a RMSE of 0.53 (all in natural log units).

In SPARROW models, inputs from each source are modified by land-to-water delivery factors, unless they are inserted directly into the stream (e.g., WWTPs), resulting in spatially variable inputs. The coefficients, associated with each source (Table 2), represent their average input; they are expressed as fractions for mass variables (e.g., farm fertilizers) or absolute quantities (kg/km^2/yr) for land-use variables (e.g., input from urban areas). On average ~20% (coefficient = 0.199) of the N from atmospheric

Table 2. Summary of MARB SPARROW models and calibration results for nitrogen and phosphorus.

Parameter	Parameter units	Coefficient units	Model coefficient value	90% confidence interval for the model coefficient		Standard error of the model coefficient	*p* value	Bootstrap estimate of coefficient (mean)
				Low	High			
Total N model								
Sources								
Atmospheric deposition	kg/yr	fraction, dimensionless	0.199	0.120	0.253	0.026	<0.0001	0.198
Wastewater treatment plants	kg/yr	fraction, dimensionless	0.762	0.446	1.082	0.146	<0.0001	0.749
Manure (confined)	kg/yr	fraction, dimensionless	0.164	0.074	0.246	0.035	<0.0001	0.162
Farm fertilizer	kg/yr	fraction, dimensionless	0.132	0.092	0.187	0.021	<0.0001	0.135
Legume crops (additional agricultural input)	kg/yr	fraction, dimensionless	0.054	−0.039	0.107	0.033	0.050	0.048
Urban and open areas	km^2	kg/km^2/yr	834	604	1193	224	0.0001	874
Land-to-water delivery								
Drainage density (log)	km/km^2	dimensionless	0.182	0.054	0.319	0.063	0.004	0.190
Irrigation (fraction of catchment with irrigation)	fraction	dimensionless	−1.837	−2.889	0.009	0.422	<0.0001	−1.774
Tiles (fraction of catchment with tiles)	fraction	dimensionless	1.361	1.062	1.661	0.167	<0.0001	1.367
Precipitation	mm/yr	mm/yr	0.001	0.001	0.002	<0.001	<0.0001	0.001
Mean air temp.	C	C	−0.057	−0.082	−0.036	0.011	<0.0001	−0.058
Soil organic matter content	fraction	dimensionless	0.035	0.012	0.062	0.016	0.026	0.036
Aquatic loss								
Stream loss (continuous)	m/d	m/d	0.049	0.029	0.064	0.006	<0.0001	0.048
Reservoir loss	m/yr	m/yr	10.82	5.19	14.15	2.09	<0.0001	10.28
Summary statistics								
RMSE		0.53						
Adjusted *R*^{2}		0.94						
Yield *R*^{2}		0.88						
Number of sites		856						
Total P model								
Sources								
Wastewater treatment plants	kg/yr	fraction, dimensionless	1.048	0.431	1.426	0.192	<0.0001	1.006
Manure (total)	kg/yr	fraction, dimensionless	0.028	0.017	0.038	0.005	<0.0001	0.028
Fertilizers (farm)	kg/yr	fraction, dimensionless	0.026	0.012	0.036	0.005	<0.0001	0.025
Urban and open areas	km^2	kg/km^2/yr	103	57.1	150	22.8	<0.0001	104
Forest and wetland areas	km^2	kg/km^2/yr	4.218	1.248	5.882	1.267	0.0005	4.020
Channel erosion	m	kg/km/yr	93.0	59.0	137	17.0	<0.0001	94.8
Deeply weathered loess soils	fraction	kg/km^2/yr	30.3	12.2	48.3	10.8	0.0026	31.2
Land-to-water delivery								
Soil permeability	cm/h	dimensionless	−0.514	−0.766	−0.250	0.107	<0.0001	−0.511
Soil organic matter content	fraction	dimensionless	0.078	0.045	0.110	0.019	<0.0001	0.078
Soil erodibility	none	dimensionless	3.309	0.091	5.778	1.257	0.009	3.081
Precipitation	mm/yr	mm/yr	0.002	0.001	0.003	<0.001	<0.0001	0.002
Mean air temp.	C	C	−0.137	−0.207	−0.079	0.023	<0.0001	−0.140
Excess overland runoff	fraction	dimensionless	0.032	0.016	0.052	0.007	<0.0001	0.033
Tile drains (fraction of catchment with tiles)	fraction	dimensionless	−1.060	−1.364	−0.678	0.275	0.0001	−1.039
Aquatic loss								
Stream loss (mean flow m^3/s < 0.14 and elevation < 1500 m)	1/d	1/d	0.745	−0.182	1.095	0.175	<0.0001	0.663
Stream loss (mean flow 0.14 < m^3/s < 1.13 and elevation < 1500 m)	1/d	1/d	0.285	0.034	0.442	0.056	<0.0001	0.276
Reservoir loss	m/yr	m/yr	16.77	5.55	23.84	3.25	<0.0001	15.68

Table 2. Continued.

Parameter	Parameter units	Coefficient units	Model coefficient value	90% confidence interval for the model coefficient		Standard error of the model coefficient	*p* value	Bootstrap estimate of coefficient (mean)
				Low	High			
Summary statistics								
RMSE		0.67						
Adjusted R^2		0.90						
Yield R^2		0.75						
Number of sites		988						

deposition, ~76% of the N from WWTPs, ~13 to 16% of the farm fertilizers and confined manure, and ~5% of the additional N from legume crops, reaches the stream. The WWTPs coefficient being <1.0 suggests that the original inputs may have been overestimated or that the model was not properly specified. On average, urban areas (not including input from WWTPs) contribute 834 kg/km^2/yr (Table 2). Estimated yields from this study are in the range of those published. Reckhow et al. (1980) conducted a literature search of export rates from selected land uses and found that annual N export from urban areas ranged from 282 to 4150 kg/km^2. Nitrogen from manure from unconfined animals and from commercial and industrial point sources were evaluated but found to be insignificant at $p < 0.05$ and were not included in the N model (discussed later). Based on the signs of the land-to-water delivery coefficients, N yields would expected to be higher in areas with more tile drainage, less irrigation, soils with higher organic matter content, more precipitation, cooler air temperatures, and a higher density of streams. Instream loss was significant, but losses decrease as flow increases. Removal/deposition in reservoirs also was significant.

The ability of the MARB N model to simulate the measured loads is demonstrated in Fig. 1A (measured and simulated loads are in the Supplemental Material). Because positive errors can become very large but negative errors are constrained by an estimated load of zero, the prediction errors are reported on a log base 2 scale (Robertson and Saad, 2011). Overpredictions of +1 and +2 indicate that the predicted values are 2× and 4× the measured value, respectively, whereas underpredictions of −1 and −2 indicate that the predicted value is 0.5× and 0.25× of the measured values, respectively. Most predictions are within ± 1 units (within 0.5× to 2.0×) of the measured values. No consistent regional biases in predictions are apparent, although relatively large errors occurred in western Iowa, eastern Nebraska, and the northwest part of the MARB.

The MARB P model had seven sources—farm fertilizers, total manure, WWTPs, urban and forested areas, channels in large streams, and deeply weathered loess soils; seven land-to-water delivery factors—fraction of stream catchments underlain by tile drains, precipitation, air temperature, excess overland runoff, and the permeability, erodibility, and organic matter content of the soil; coefficients for P removal in small and intermediate-sized streams; and one factor describing removal in reservoirs (Table 2). Coefficients for all sources and factors were highly significant ($p \leq 0.009$). The coefficients were also robust (small SEs, narrow 90% confidence intervals, and mean bootstrap estimates within 10% of the NLLSR estimates; Table 2). This model explained 90 and 75% of the variances in the 988 monitored loads and yields, respectively, and had an overall RMSE of 0.67 (all in natural log units).

The source coefficients indicate that ~100% of the P from WWTPs (coefficient of 1.048 in Table 2) and ~3% of the P in farm fertilizers and manure reach the stream. On average, forested areas contribute ~4 kg/km^2/yr compared with ~103 kg/km^2/yr from urban areas. Published annual P exports from forested areas ranged between 2 and 83 kg/km^2 compared with 19 to 623 kg/km^2 from urban areas (Reckhow et al., 1980); therefore, estimated yields are in the range of those published. Additional P was contributed by channels in large streams and from deeply weathered loess soils primarily in Mississippi, eastern Tennessee, and Kentucky. Phosphorus from commercial and industrial point sources was evaluated but found to be insignificant at $p < 0.05$ and not included in the P model. Based on the signs of the land-to-water delivery coefficients, P yields would expected to be higher in areas with less tile drainage, more overland runoff, more precipitation, cooler air temperatures, and with soils that are more erodible, less permeable, and higher in organic matter content. Instream loss was significant in small and intermediate-sized streams (mean average annual flows <0.14 m^3/s and 0.14 to 1.13 m^3/s, respectively), but statistically insignificant at $p < 0.05$ in large streams (mean average annual flow >1.13 m^3/s) and streams at elevations higher than 1500 m. A single factor describing P removal in streams that is a continuous function of the time of travel was evaluated, but not used because large streams were found to be net sources of P. Removal/deposition in reservoirs also was significant.

The ability of the P model to simulate measured loads is demonstrated in Fig. 1B. Most predictions are within ±1 unit (0.5× to 2.0×) of measured values. The only consistent regional biases are in central South Dakota, Oklahoma, and Colorado where loads were underpredicted, and in western Kansas, where the loads were overpredicted. There was, however, a relatively strong west-east difference in the magnitude of the residuals, demonstrating less precision in the west.

Incremental Nutrient Yields

Incremental N and P yields from each model catchment are shown in Fig. 2. An incremental yield is the load generated within a catchment divided by its incremental area, and only adjusted for attenuation in streams and reservoirs in that reach. Incremental yields are mediated by the amount and type of nutrients supplied to the catchment and by land-to-water delivery factors. Mean and median incremental annual N yields were 779 and 455 kg/km^2, respectively (SD = 3550 kg/km^2) (Table 3). Mean and median incremental annual P yields were 70.9 and 38.5 kg/km^2, respectively (SD = 432 kg/km^2). Large standard deviations indicate that the yields are highly skewed. Some catchments have several sources, but others are dominated by one source (as demonstrated by the

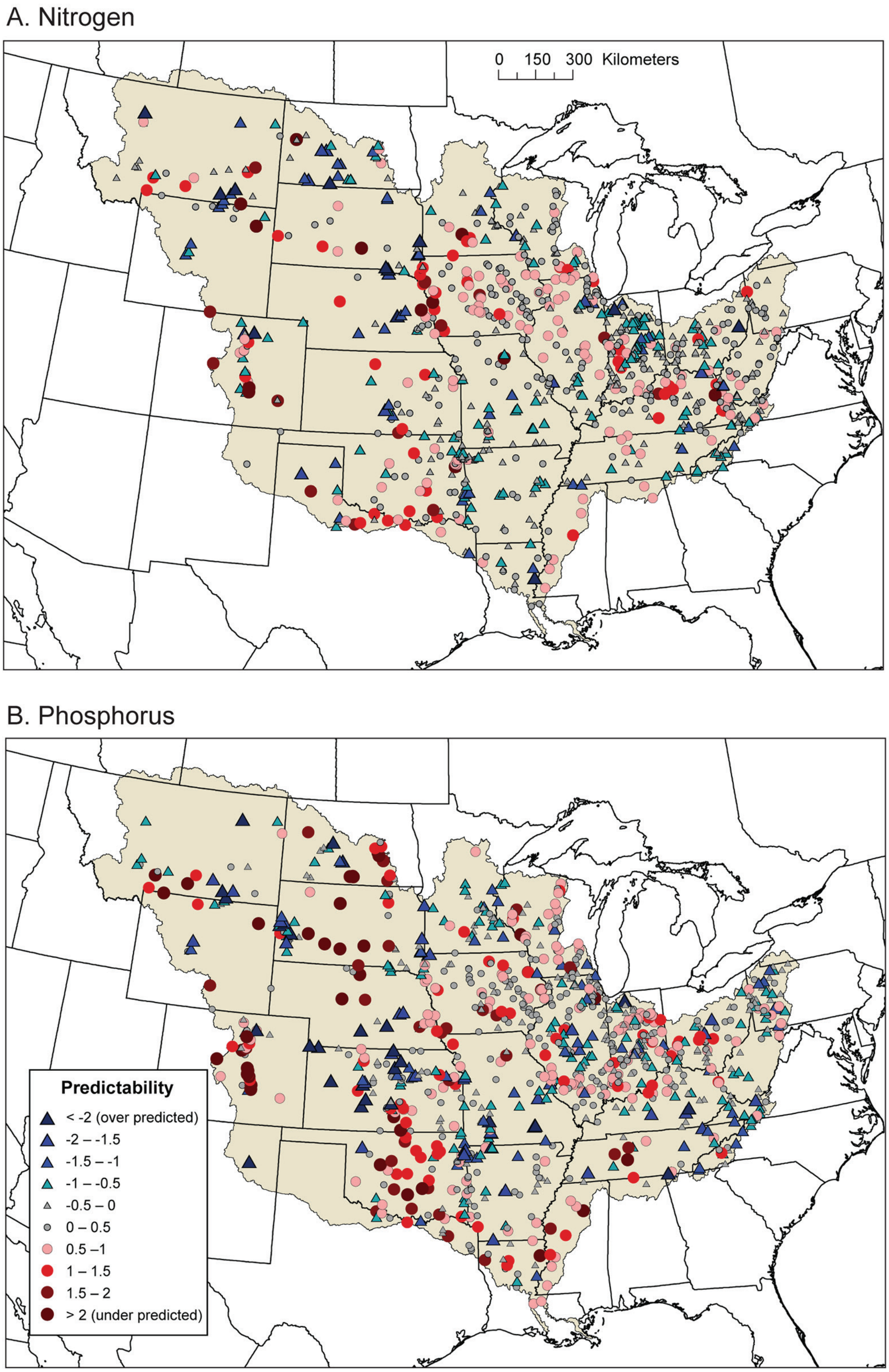

Fig. 1. Predictability of the Mississippi/Atchafalaya River Basin SPARROW models for (A) nitrogen and (B) phosphorus. The predictability is expressed as the number of doublings (overprediction, positive values and upward pointing triangles) or foldings (underprediction, negative values and circles) of the measured loads at each site.

range in the importance of sources in Table 3). Highest annual incremental yields (>8000 kg N/km^2 and >1000 kg P/km^2) were from catchments dominated by WWTPs. Lower but still relatively high annual N (1660–8000 kg/km^2) and P yields (133–1000 kg/km^2) were primarily from catchments in intense crop-oriented agricultural areas of the central Mississippi and Ohio RBs for N, but more widely distributed for P (Fig. 2). Differences in N and P yields were related to differences in land use: N yields were highest in areas with crop-oriented agriculture, and P yields were highest in areas with crop and animal agriculture. Areas with highest P yields occurred further south as compared to those with the highest N yields (southern Illinois, central Missouri,

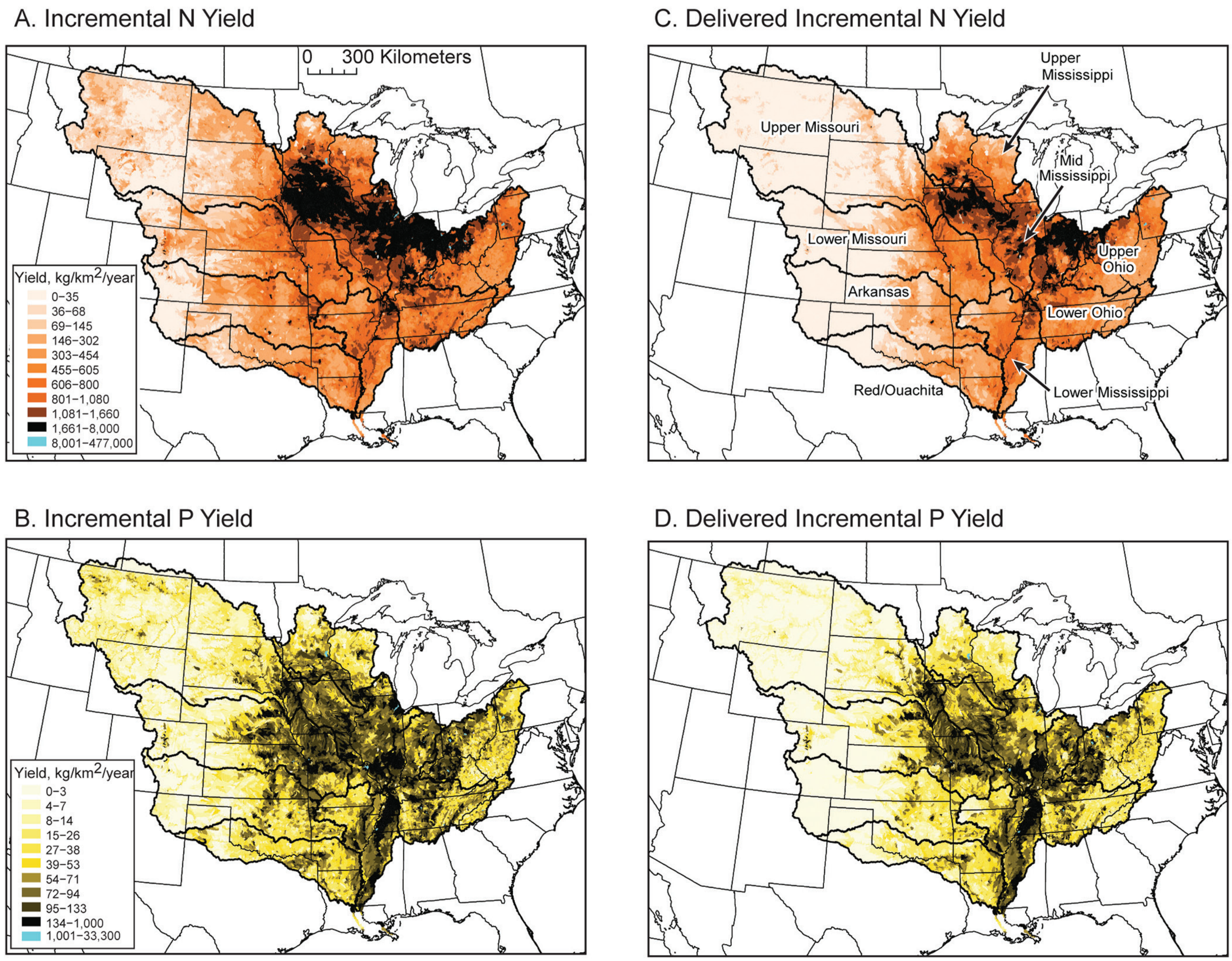

Fig. 2. Distribution of incremental annual yields to the end of the catchment for (A) nitrogen and (B) phosphorus and delivered increment annual yields to the Gulf of Mexico for (C) nitrogen and (D) phosphorus for the SPARROW catchments within the Mississippi/Atchafalaya River Basin, MARB. The nine main river basins in the MARB defined by Goolsby et al. (1999) are labeled in (C).

and southwestern Iowa). The total long-term, average-annual, detrended (to 2002), nondecayed (not including losses in transport beyond the original reach) N and P loads in streams throughout the entire MARB were 2,532,000 tonnes (t) of N and 189,000 t of P (Table 4).

Nutrient Delivery from the MARB

The total delivered load/yield to the Gulf is also mediated by losses that occur in downstream transport. SPARROW predicts the delivery to the Gulf from each incremental catchment outlet, accounting for instream and reservoir losses along the flowpath. The spatial arrangement of the nutrient sources, with respect to the transport distance and the presence and location of reservoirs, can affect the final delivered loads. The total long-term, average-annual, detrended N load and yield delivered to the Gulf of Mexico were estimated to be 1,351,000 t and 423 kg/km^2, respectively (Table 4). The total delivered P load and yield were estimated to be 124,000 t and 38.8 kg/km^2, respectively. Therefore, 53% of the N reaching the end of SPARROW catchments is transported to the Gulf of Mexico compared to 66% of the P. For comparison, annual N and P loading from the MARB is monitored at the Mississippi River at St. Francisville, LA, and Atchafalaya River at Melville, LA, by the USGS (2012). For 1980 to 2007, the average annual total N and P loads from the MARB were 1,410,000 and 139,000 t, respectively; however, these loads were not detrended to 2002.

Distributions in delivered incremental N and P yields from the MARB are shown in Fig. 2C,D. Major differences in the distributions in the incremental and delivered incremental yields were that delivered yields from the western part of the MARB were lower and they had a slightly more apparent dendritic pattern. Mean and median delivered incremental annual N yields were 609 and 363 kg/km^2, respectively (SD = 1060 kg/km^2) (Table 3). Mean and median delivered incremental annual P yields were 44.0 and 26.4 kg/km^2, respectively (SD = 76.1 kg/km^2). Similar to nondecayed yields (Fig. 2A,B), highest delivered yields (Fig. 2C,D) were from catchments dominated by WWTPs, and lower but still relatively high annual yields were from catchments in intense agricultural areas of the Middle Mississippi and Ohio River RBs for N, but more widely distributed for P.

For the nine main RBs, annual delivered N and P loads were highest from the Middle Mississippi RB (337,000 and 23,300 t, respectively) and lowest from the Arkansas RB (48,900 and 5530 t, respectively) (Table 4). After compensating for basin

Table 3. Summary statistics of estimated annual yields and source shares from incremental catchments in Mississippi/Atchafalaya River Basin.

Variable	Total nitrogen							Total phosphorus						
	Mean	SD	Percentiles					Mean	SD	Percentiles				
			10th	25th	Med. †	75th	90th			10th	25th	Med.	75th	90th
	Yield													
	kg/km^2													
Incremental yield‡	779	3550	35	98	455	922	1660	70.9	432	3.0	9.6	38.5	81.9	133
Delivered incremental yield§	609	1060	22	56	363	766	1520	44.0	76.1	2.5	6.8	26.4	64.4	105
	Source shares¶													
	%													
Atmospheric deposition	45.3	27.9	15.0	21.1	37.6	67.6	89.9	–#	–	–	–	–	–	–
Wastewater treatment plants	1.9	9.0	0.0	0.0	0.0	0.0	1.9	2.8	11.1	0.0	0.0	0.0	0.0	4.4
Manure (confined)	7.0	9.3	0.0	0.6	3.7	9.6	18.3	–	–	–	–	–	–	–
Manure (total)	–	–	–	–	–	–	–	27.6	22.0	2.4	9.3	23.3	41.3	59.3
Farm fertilizer	29.1	22.2	0.3	7.5	28.0	48.8	59.5	18.9	18.9	0.1	2.3	12.7	31.6	48.3
Legume crops (additional agricultural input)	7.0	7.9	0.0	0.6	4.6	11.5	16.3	–	–	–	–	–	–	–
Forested land	–	–	–	–	–	–	–	12.4	20.3	0.2	0.8	3.6	13.0	40.7
Urban and open areas	9.6	11.1	0.0	3.4	6.3	11.9	20.5	16.5	15.5	0.0	6.5	12.8	21.8	35.8
Channel erosion	–	–	–	–	–	–	–	19.9	28.3	0.0	0.0	0.0	34.2	69.5
Deeply weathered loess soils	–	–	–	–	–	–	–	1.8	9.1	0.0	0.0	0.0	0.0	0.0

† Med, median (50th percentile).

‡ The amount of nitrogen, N, or phosphorus, P, generated within a given incremental catchment that makes it to the catchment outlet, and incorporates the effects instream and inreservoir attenuation in that particular reach.

§ The amount of N or P generated within a given incremental catchment that is ultimately delivered to the Gulf of Mexico.

¶ The amount (share) of N or P, in percent, generated within a given incremental catchment that can be attributed to the sources in the model.

–, not in the model.

Table 4. Total annual delivered load and yields for the Mississippi/Atchafalaya River Basin and nine main river basins, with the percentage of the load/yield attributed to each source.

River basin	Total nondecayed N load	Total delivered N load	Total delivered N yield	Percentage of total N load/yield					
				WWTPs†	Urban areas	Atmospheric deposition	Fertilizers (farm)	Manure (confined)	Legume crops (additional agricultural input)
	t	t	kg/km^2	%					
Upper Ohio	291,000	187,000	751	13.9	10.8	37.3	25.9	6.3	5.8
Lower Ohio	405,000	286,000	1024	5.3	7.5	28.0	41.3	9.3	8.5
Upper Missouri	231,000	62,500	77	3.2	4.8	18.4	45.9	13.8	13.9
Lower Missouri	301,000	128,000	250	5.1	6.2	21.6	47.6	10.6	9.0
Upper Mississippi	286,000	129,000	580	4.1	5.7	21.7	37.5	18.9	12.1
Middle Mississippi	601,000	337,000	1226	8.1	5.6	16.9	47.8	9.8	11.9
Arkansas	157,000	48,900	119	7.1	9.1	32.1	32.1	17.1	2.5
Lower Mississippi	148,000	112,000	603	4.4	6.9	30.4	47.2	4.4	6.8
Red/Ouachita	104,000	53,200	221	3.9	9.8	39.1	31.5	13.9	1.8
Total MARB	2,532,000	1,351,000	423	7.1	7.2	25.7	40.8	10.2	9.0

River basin	Total nondecayed P load	Total delivered P load	Total delivered P yield	Percentage of total P load/yield						
				WWTPs	Urban areas	Fertilizers (farm)	Manure (total)	Forests	Instream channels	Deeply weathered loess soils
	t	t	kg/km^2	%						
Upper Ohio	18,700	15,300	61.4	19.8	23.7	16.1	16.0	5.9	18.5	0.0
Lower Ohio	25,300	20,100	72.0	13.4	16.8	30.7	20.0	3.5	14.1	1.5
Upper Missouri	23,500	9,050	11.1	5.8	11.9	32.5	34.3	2.1	13.4	0.0
Lower Missouri	31,100	20,400	39.8	9.3	14.0	28.4	27.6	1.6	10.8	8.3
Upper Mississippi	14,400	7,600	34.3	16.6	13.3	25.9	27.3	4.3	12.7	0.0
Middle Mississippi	32,200	23,300	85.0	17.3	15.1	34.5	19.4	1.4	9.8	2.6
Arkansas	14,200	5,530	13.5	12.3	16.6	17.2	34.0	2.5	17.4	0.0
Lower Mississippi	17,500	15,700	84.6	7.3	13.8	26.9	8.9	4.0	14.2	24.8
Red/Ouachita	11,300	6,320	26.3	4.6	19.8	15.4	28.9	8.5	22.8	0.0
Total MARB	189,000	124,000	38.8	12.8	16.1	27.0	21.7	3.3	13.7	5.3

† WWTPs, wastewater treatment plants.

size, annual N yields ranged from 1230 kg/km^2 from the Middle Mississippi RB to 77 kg/km^2 from the Upper Missouri RB (Table 4 and Fig. 3). Annual delivered P yields ranged from about 85 kg/km^2 from the Middle and Lower Mississippi RBs to 11.1 kg/km^2 from the Upper Missouri River RB.

Sources of Nutrients

Important N sources in the MARB, as identified by the MARB SPARROW model, include farm fertilizers, manure from confined animals, additional agricultural input from legume crops, atmospheric deposition, WWTPs, and urban areas (Fig. 4 and Table 3). This model did not specifically identify contributions from unconfined animal operations, commercial and industrial point sources, forested areas, or natural/background sources (discussed later); therefore, inputs from these sources would be incorporated into other defined sources or represented as model error. Overall, agricultural inputs (manure, fertilizer, and legume crops) were the largest N source (60% of the total), with farm fertilizers contributing 41% of the total (Table 4). Atmospheric deposition, which may include volatilized losses from natural, urban, and agricultural sources, contributed 26%, and urban sources contributed about 14% (7% from urban areas and 7% from WWTPs).

Important P sources in the MARB, as identified by the MARB SPARROW model, include farm fertilizers, total manure, WWTPs, urban and forested areas, channels in large streams, and deeply weathered loess soils (Fig. 4). This model did not specifically identify contributions from atmospheric deposition,

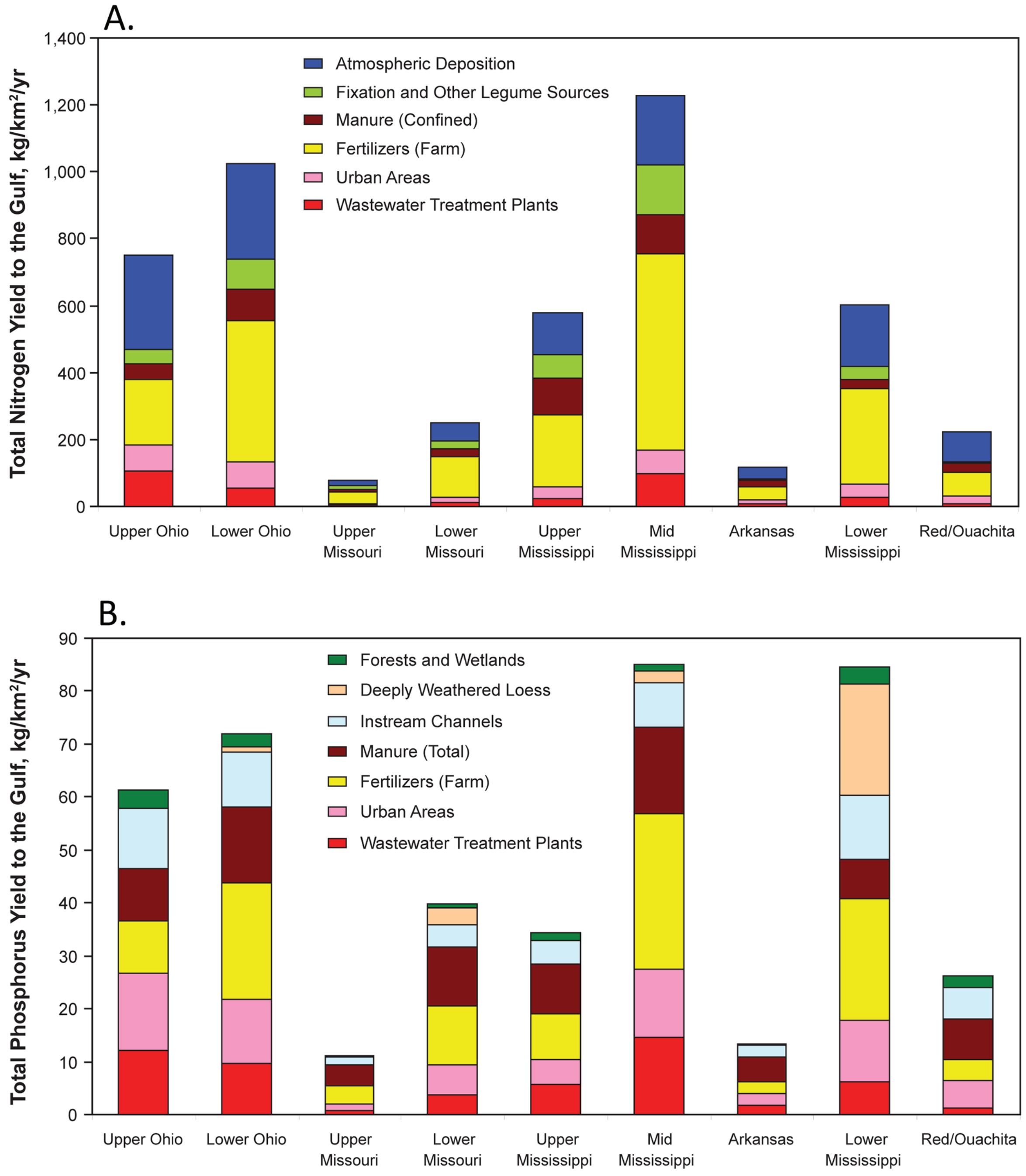

Fig. 3. Total annual delivered annual yields from each main river basin in the Mississippi/Atchafalaya River Basin for (A) nitrogen and (B) phosphorus. Yields are subdivided based on the input of each source.

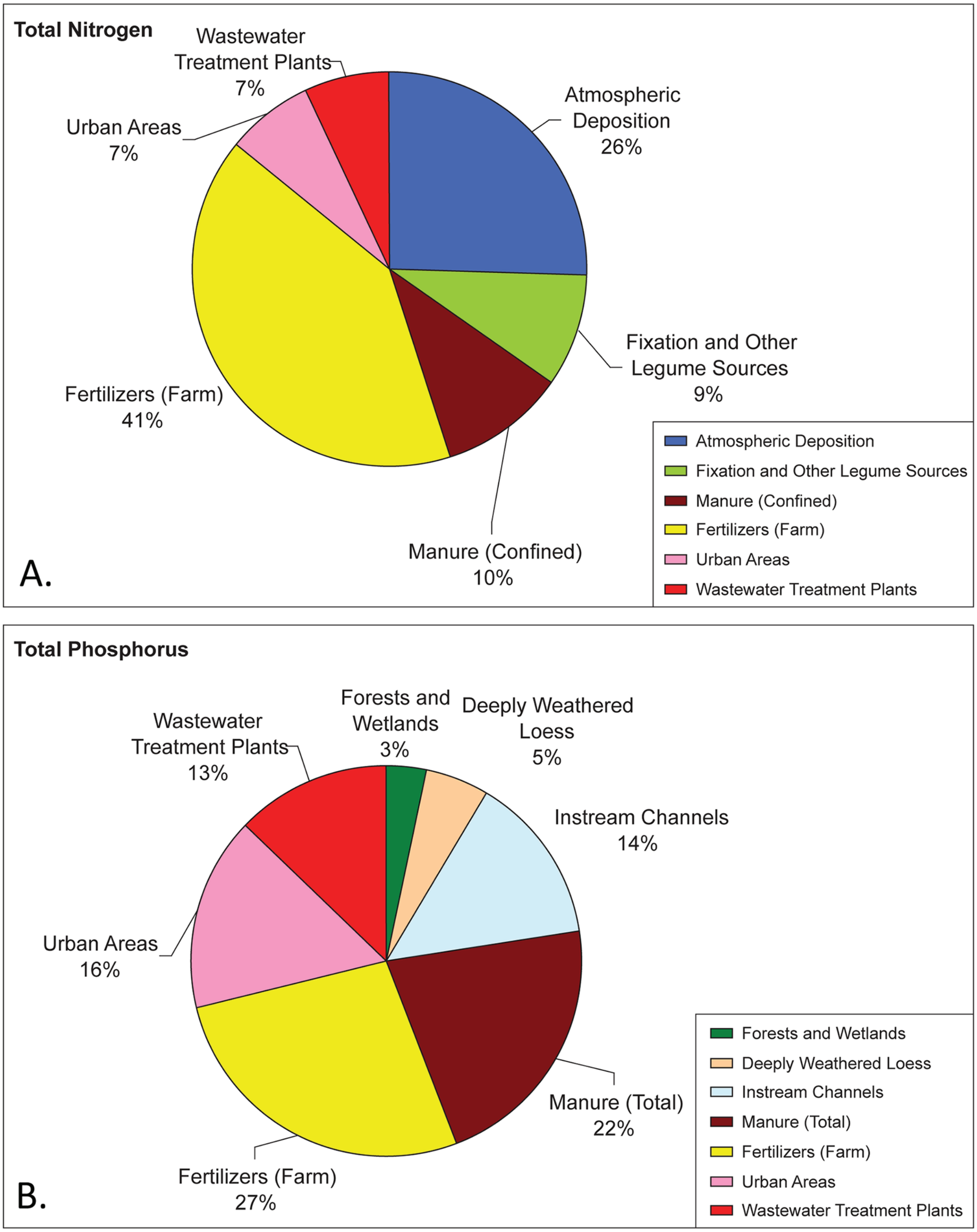

Fig. 4. Sources of nutrients to the Gulf of Mexico for (A) nitrogen and (B) phosphorus.

commercial and industrial point sources, or natural background sources; therefore, they would be incorporated into the other defined sources or represented as model error. Agricultural inputs (manure and fertilizers) were the largest P source (49% of the total—27% from farm fertilizers and 22% from manure; Table 4). Urban sources contributed 29% (16% from urban areas and 13% from WWTPs); commercial and industrial point sources would most likely be taken into account in the urban-area term. This model also identified inputs from other background sources (forests, 3%; and deeply weathered loess soils, 5%) and erosion of channels and streambanks of large streams where P was previously deposited from other upstream sources (14%).

To better describe how the importance of the sources of N and P differ throughout the MARB, the load was subdivided among major sources (agricultural sources, urban sources, and other mixed sources) at the SPARROW catchment level. At this level, sources were of relatively similar importance for N and P (Fig. 5). Agricultural sources dominated in most areas; however, urban sources were most important around metropolitan areas. Other mixed sources (atmospheric input for N, and inputs from channels, forests, and deeply weathered loess soils for P) were

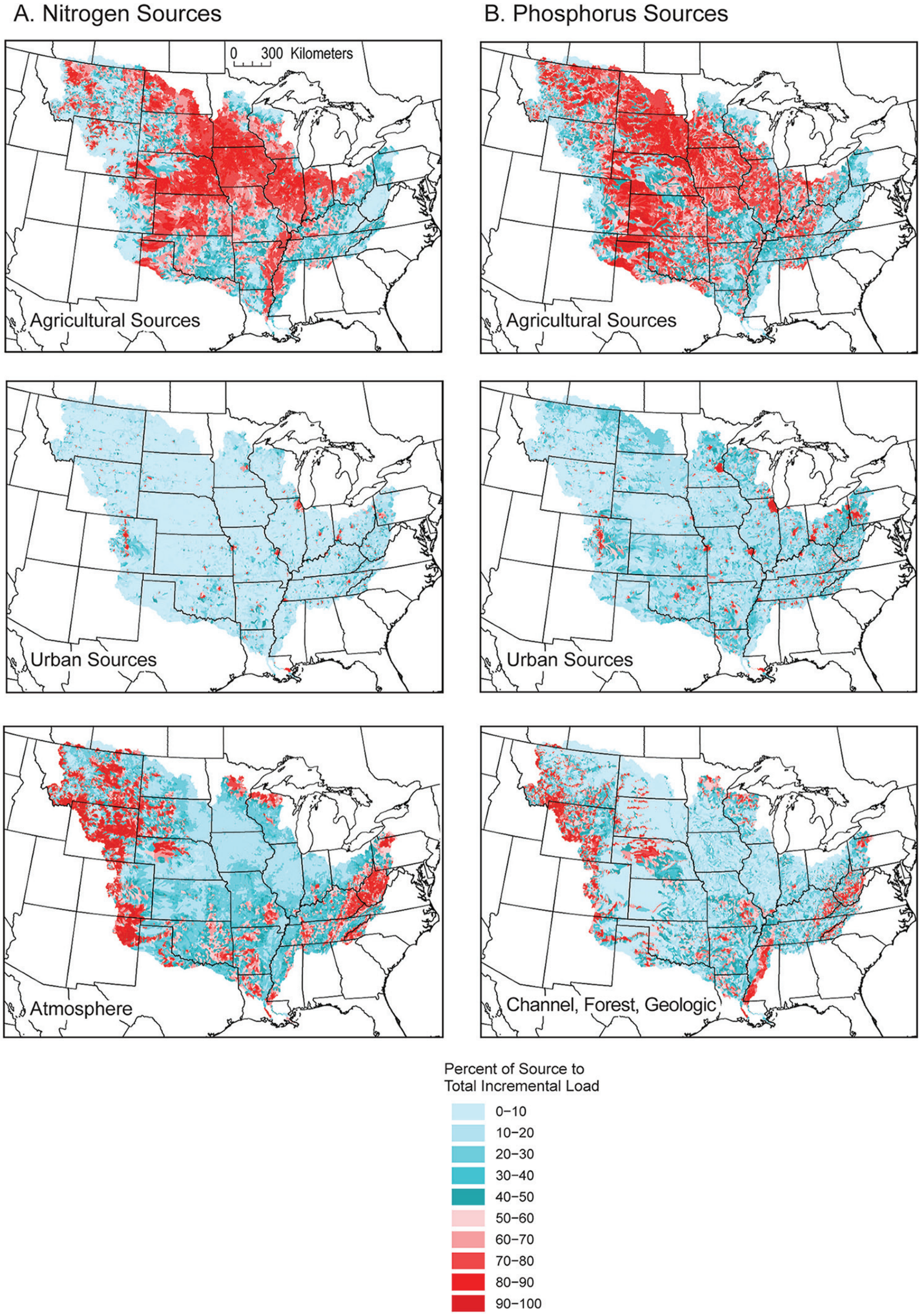

Fig. 5. Spatial distribution in the relative importance of major sources of nutrients in SPARROW catchments throughout the Mississippi/Atchafalaya River Basin for (A) nitrogen and (B) phosphorus.

most important in the extreme north, west, and east areas of the MARB; however, many of these areas had limited inputs from other sources.

The importance of the N and P sources differed among RBs (Fig. 3, Table 4, and Supplemental Material). Urban areas and WWTPs were most important for the Upper Ohio RB, which has the most extensive metropolitan areas (contributing 44% of the P and 25% of the N), and least important for the Upper Missouri RB (contributing 18% of the P and 8% of the N). Agricultural sources were most important for RBs in the central part of the MARB (especially the Missouri and Upper and Middle Mississippi RBs). For N, fertilizers were the most important source for all of the RBs, whereas for P, generally a mixture of sources was important. Phosphorus from manure was most important for the Upper Missouri and Arkansas RBs. Atmospheric deposition of N was most important for the Upper Ohio RB; this area does not have particularly high deposition rates, but deposition stands out because other sources of N are small. Instream channels are an important source in the Ohio, Red, and Middle and Lower Mississippi RBs (Fig. 3). Phosphorus from erosion of deeply weathered loess soils was important only for the Lower Mississippi RB.

The importance of the various agricultural sources (fertilizers, manure, and other agricultural sources) varied throughout the MARB (Fig. 6). For N, farm fertilizer was the dominant source throughout most agricultural areas, with manure being

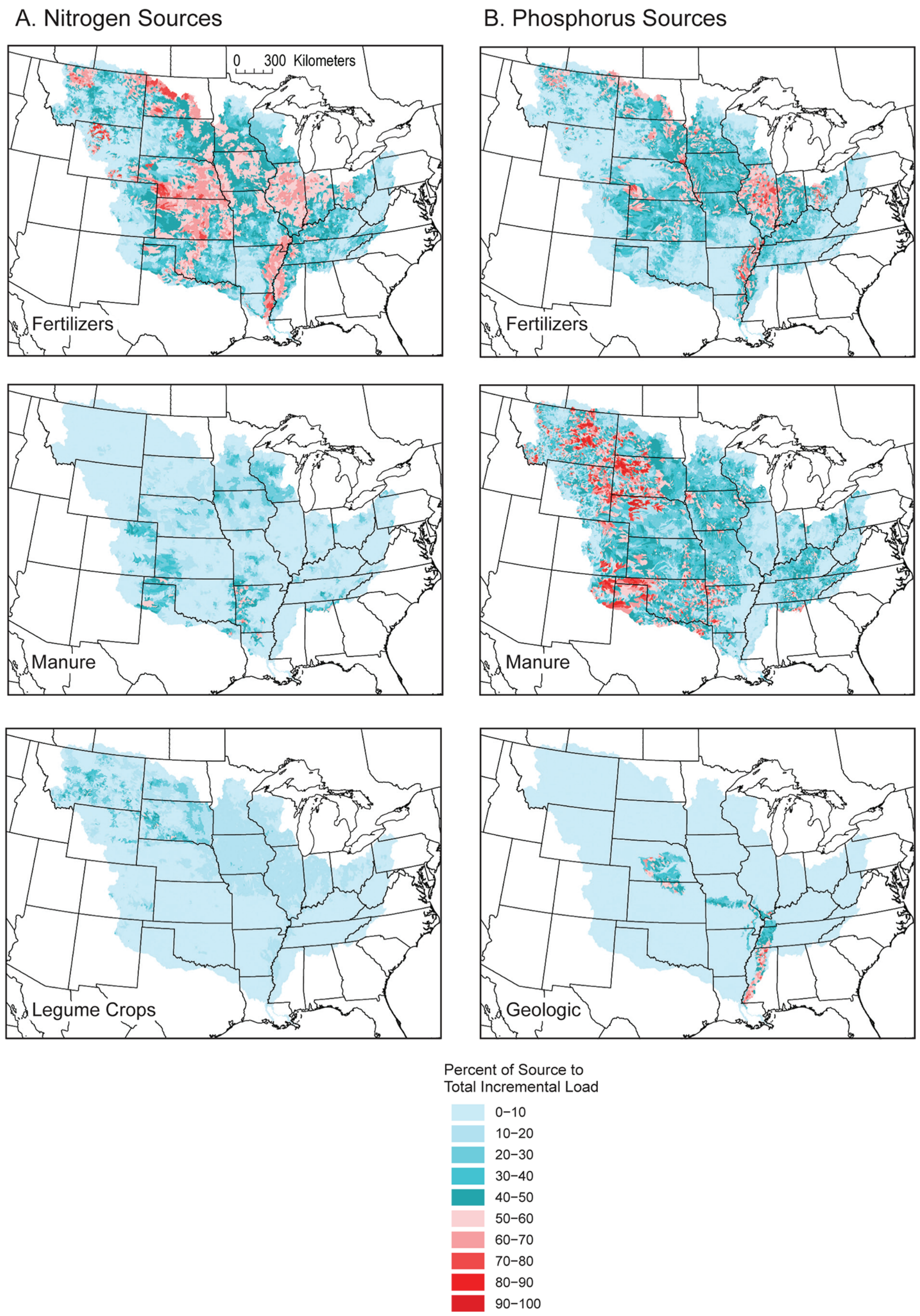

Fig. 6. Spatial distribution in the relative importance of agricultural and geologic sources of nutrients in SPARROW catchments throughout the Mississippi/Atchafalaya River Basin for (A) nitrogen and (B) phosphorus.

moderately important only in western Arkansas and northern Texas, and additional inputs from legume crops being moderately important in the northwest part of the MARB. For P, farm fertilizers were most important in Illinois, along the Mississippi River, and in the extreme northern part of the MARB. Phosphorus from manure was the most important source in most agricultural areas in the western part of the MARB. Phosphorus from the erosion of deeply weathered loess soils, predominantly found in agricultural areas, was a dominant source along the eastern side of the Mississippi River. Thus, although agriculture was the dominant sources of both N and P, their specific types of sources differ greatly.

Discussion

Nitrogen and Phosphorus Sources and Delivery

The highest N and P yields were from catchments dominated by WWTPs; however, intense agricultural areas also produced high N and P yields (Fig. 2). Differences in geographic patterns in N and P can be explained primarily by differences in land use and the difference in the dominant sources of N and P (Table 1). Nitrogen yields were highest in areas with crop-oriented agriculture (primarily associated with areas of high farm fertilizer input rates) in the Corn Belt, whereas highest P yields were in areas with crop- and animal-oriented agriculture (including areas with high manure input rates), which are more widely distributed. The increased land-to-water delivery of N compared with P results from higher N inputs (Table 1) and increased delivery rates to streams. The mean rate of delivery of N from fertilizers and manure to streams (13–16%) is about sixfold higher than that for P (about 2.7%; coefficients in Table 2). This difference in land-to-water delivery reflects intrinsic differences in crop nutrient requirements and the chemical forms and transport pathways for N and P (Alexander et al., 2008). The large nutrient requirements for corn and the potential for N overapplication contribute to the leaching of nitrate N, which is highly mobile in soils and groundwater (Howarth et al., 1996).

The coefficients associated with tile drains indicate that tile drains may increase the delivery of N to streams but decrease the delivery of total P. Tile drainage has been shown to increase the delivery of soluble nutrients (such as nitrate) to surface waters because of the rapid conveyance of drainage water that has leached nutrients from the upper soil profile (David et al., 1997). Tile drainage, however, tends to reduce surface runoff from an area and thus, although possibly increasing the delivery of soluble P, decreases delivery of sediment and sediment-bound nutrients such as particulate P to surface-water bodies (Zucker and Brown, 1998).

Nitrogen in manure from unconfined animals was evaluated but found to be insignificant at $p < 0.05$; therefore, it was not included in the N model. This was also found to be a nonsignificant source in previous SPARROW models by Robertson and Saad (2011). The negligible importance of N from manure from unconfined animals may be valid because much of this N may be volatilized before runoff from the fields (Meisinger and Jokela, 2000; Diebel et al., 2009). Meisinger and Jokela (2000) found that close to 100% of the ammonia was lost due to volatilization when manure was not injected or incorporated into the soil. Therefore, redeposited N may be included with atmospheric deposition contributions. Much of the N lost in downstream transport occurs in streams because of denitrification and other instream processes (Alexander et al., 2008), whereas much of the P loss occurs as deposition in reservoirs; P has a higher loss rate in reservoirs than N (coefficients in Table 2). As a net result of these differences in transport, 53% of the N reaching the end of SPARROW catchments is transported to the Gulf of Mexico compared with 66% of the P (Table 4).

SPARROW models can be used simulate the effects of changes in nutrient inputs. A Web-based decision support system (DSS) has been developed to provide access to SPARROW simulation results on stream water-quality conditions and to offer scenario testing capabilities for research and water-quality planning via a graphical user interface (Booth et al., 2011). Reductions in inputs from point sources may have an almost immediate effect on the water quality of receiving streams and downstream waters. Reductions in other nutrient sources, however, may have significant lags between when actions are taken, such as fertilizer reductions, and when changes in water quality are expected to occur in streams (Tesoriero et al., 2013). Scenarios simulated with the SPARROW DSS, therefore, represent changes in water quality that should occur when the system reaches a new equilibrium. The MARB SPARROW model described here can be accessed through the DSS at http://cida.usgs.gov/sparrow/.

Comparison of Source Shares with Previous Studies

Understanding the relative importance of N and P sources in specific areas is important to determine the types of actions needed to limit nutrient inputs to streams. Different modeling methods will invariably arrive at different conclusions about the nature of nutrient sources in watersheds because of underlying differences in data inputs, process assumptions, and various structural components of the models being used. A few studies have examined the sources of N and P in the MARB; however, each study had a slightly different classification of the sources. Therefore, to allow comparisons among studies, N sources from these studies were combined into the following categories: agricultural sources—further subdivided into farm fertilizers, manure, and additional inputs from legume crops; atmospheric deposition and forests; and WWTPs and urban areas. Phosphorus sources were combined into inputs from agricultural sources—further subdivided into fertilizers and manure; instream channels, soils, and forests; and WWTPs and urban areas (Table 5). In some studies, it was difficult to separate some of the sources into these categories, but an effort was made to make as similar classification as possible.

Goolsby et al. (1999) used multiple-regression techniques to determine the relative importance of various sources to the overall loading from the MARB for 1980 to 1996 by developing yield relations that were a function of the various sources. They found the following breakdown for N: agricultural sources (65%, with fertilizers [50%], manure [15%]), atmospheric deposition and forests (24%), and WWTPs effluent (11%); and for P: agricultural sources (48%, with fertilizers [31%], manure [17%]), other factors represented by runoff (42%, categorized as instream/soils/forests), and WWTPs effluent (10%) (Table 5). In their regression equation, the coefficient for N input from fixation was negative and statistically insignificant; therefore, they assumed the input from fixation was minimal. The main difference from the results of the present study is that their N inputs from fixation and other legume sources may have been allocated to other agricultural sources, and much of their P inputs from urban areas may have been allocated to the other factors represented by runoff category.

David et al. (2010) and Jacobson et al. (2011) also used multiple-regression techniques to determine which inputs and environmental characteristics (variables describing nutrient inputs, land use, and tile drainage) were most important in describing average (1997–2006) January through June yields. The regression relations, which were developed using 153 sites for nitrate and 101 sites for P, were used to estimate N and P yields from the 1768 counties in the MARB. Based on significant variables in their final regression equation, David et al. (2010) concluded that fertilized corn on tile-drained watersheds was the dominant source of nitrate to the Gulf, WWTPs effluent had localized effects, and atmospheric deposition and manure were not significant explanatory variables. Based on significant variables in their final regression equations, Jacobson et al. (2011) concluded that the area of cropland, fertilizer inputs, and P consumed by humans were the dominant P sources. Manure was not a significant explanatory variable in their regression relations and thus they concluded that manure was not a significant contributor of P. Results from these studies only enabled the relative importance of the various sources to the regression relation to be determined and did not enable the relative inputs from the various sources to be computed.

Previous SPARROW models (Smith et al., 1997; Alexander et al., 2008) were also used to quantify the relative importance of the nutrient sources in the MARB. Smith et al. (1997) used similar types of inputs to those used in this study but quantified inputs for 1987. They found the following breakdown for N sources: agricultural sources (74%, with fertilizers [66%], manure [8%]), atmospheric deposition/forests (18%), and WWTPs effluent (7%); and for P: agricultural sources (77%, with fertilizers [37%], manure [40%]), forests (11%), and WWTPs effluent (12%) (Table 5). Their N model did not have a term for fixation and other legume sources; therefore, it would have been incorporated into the other sources, presumably agricultural sources. The main difference in the results of the 1987 Smith et al. SPARROW N model and the MARB N model was that farm fertilizers were much more important than found in this study and appeared to reduce the importance of all other terms. Results from the Smith et al. P model were different than those found with the MARB P model for all categories. Their P model indicated that agricultural sources represented 77% of the total, compared with only ~50% indicated by our MARB model.

Alexander et al. (2008) used SPARROW models with different types of nutrient inputs from those used by Smith et al. (1997). The SPARROW models by Alexander et al. (2008) were designed to separate the inputs from various crop types and land uses rather than separate the inputs from specific nutrient sources, and used inputs similar to 1992 and 2002. After combining the inputs from all agricultural crops, the following breakdown for N was found for the Alexander et al. (2008) study with 1992 inputs: agricultural inputs, ~69% (with fertilizers and captured manure applied to all agricultural crops collectively accounting for 64% [captured manure represents that collected from confined animals and applied to crops], and uncaptured manure accounting for 5% [that lost in feedlots and from unconfined animals]); atmospheric deposition/forests, 22%; and urban inputs, 9% (Table 5). The following breakdown was found for P with 1992 inputs: agricultural inputs, ~80% (with fertilizers and captured manure applied to all agricultural crops accounting for 42%, and uncaptured manure accounting for 38%); forests, 9%; and urban inputs, 12%. Relatively similar results were found by Alexander et al. (2008) for 2002. The main difference from the MARB N model was that the Alexander et al. (2008) models combined farm fertilizers, captured manure (relatively large fraction of the manure), and fixation and applied these inputs to the various crop types, which were then used to obtain these estimates. Collectively, their agricultural sources represented 67 to 69% of the N, compared with 60% in this study. Therefore, although Alexander et al.'s (2008) N model was not designed to separate the individual agricultural sources, the results are fairly similar. Results from the Alexander et al. (2008) P models were different than those found with the MARB model for all general categories. Alexander et al. (2008) found nonrecoverable manure (nonrecoverable manure from animals in pasture and rangeland, and lost from feedlots) was the most important source of P (~39%), which was more important than found for total manure in this study (21.7%). Contributions of P from manure was actually more important in Alexander et al.'s (2008) models than presented in Table 5 because their modeling

Table 5. Comparison of the allocation of nutrient load by source among studies.

Nitrogen

Study	Time period	Source shares		Manure	Legume crops (additional agricultural input)	Atmospheric deposition/ forests	WWTPs† and urban areas
		Agricultural sources	Farm fertilizers				
		——— % ———					
Goolsby et al. 1999	1980–1996	65.0	50.0	15.0	0.0	24.0	11.0
Smith et al. 1997	1987	74.0	66.0	8.0	0.0	18.0	7.0
Alexander et al. 2008	1992	69.2	63.8‡	5.4§	0.0‡	21.8	9.0
Alexander et al. 2008	2002	66.8	61.1‡	5.7§	0.0‡	22.9	10.3
White et al. 2013	1960–2006	80.0	NA¶	NA	NA	NA#	13.0
This study	2002	60.0	40.8	10.2	9.0	25.7	14.3

Phosphorus

Study	Time period	Source shares		Manure	Instream/soils/ forests	WWTPs and urban areas
		Agricultural sources	Farm fertilizers			
		——— % ———				
Goolsby et al. 1999	1980–1996	48.0	31.0	17.0	42.0	10.0
Smith et al. 1997	1987	77.0	37.0	40.0	11.0	12.0
Alexander et al. 2008	1992	79.9	41.6‡	38.3§	8.6	11.5
Alexander et al. 2008	2002	78.6	39.0‡	39.6§	8.7	12.7
White et al. 2013	1960–2006	61.0	NA	NA	11.0	28.0
This study	2002	48.7	27.0	21.7	22.4	28.9

† WWTPs, wastewater treatment plants.

‡ Farm fertilizers actually represent inputs from farm fertilizers, captured manure, and fixation (for N).

§ Manure actually represents inputs from only uncaptured manure from unconfined animals and feedlot loss, and other captured manure is included with farm fertilizers.

¶ NA, not available.

Atmospheric deposition was not provided as an individual source.

framework did not allow us to remove manure recovered from confined animals from other inputs to agricultural crops; we included this part of the manure in their farm fertilizer term. Therefore, the importance of manure was more than twice that found in the present study. They also found that inputs from urban sources were much less important than found in this study (12–13% compared with 29% found in this study). Inputs from urban sources, including WWTPs, in the Alexander et al. (2008) models were based solely on the population rather than estimated inputs from WWTPs and urban areas.

White et al. (2013) used APEX and SWAT models to evaluate the sources and delivery of N and P from throughout the MARB. They partitioned the inputs into that from cropland, grassland, point sources, urban nonpoint sources, forested areas, and other sources. They found the following breakdown for N: agricultural sources, 80% (58% from cropland and 22% from grassland); and WWTPs and urban areas, 13%. They found the following breakdown for P: agricultural sources (61%, with 46% from cropland and 15% from grassland); and WWTPs and urban areas, 28%. The main differences from the MARB SPARROW models was that the White et al. (2013) models combined all agricultural sources (fertilizers, manure, and additional inputs from legume crops) and did not include atmospheric deposition as a separate source term. Therefore, the White et al. (2003) models did not allow contributions from each agricultural source to be separated, and contributions from atmospheric deposition would be incorporated into the other N sources, which probably caused agricultural sources to be more important than found with the MARB SPARROW models (80% compared with 60%). The MARB P model also included a geologic source term occurring primarily in agricultural areas; therefore, this source would have probably been included in agricultural source term in White et al.'s (2013) model. Both studies estimated similar inputs from WWTPs and urban areas (~29%).

The USEPA Science Advisory Board–Hypoxia Advisory Panel (SAB; USEPA, 2007; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008) and Jacobson et al. (2011) concluded that contributions from all point sources were more important than previously estimated in most studies and that point sources may represent as much as 22 and 34% of the total average annual N and P flux, respectively, of which WWTPs represent about 17% (206,000 t) of the total annual N flux and 25% (38,200 t) of the total P flux. This conclusion assumed that 100% of all point sources from 2004 were exported to the Gulf of Mexico; that is, there were no instream losses. In our study, 2002 WWTPs effluent represented only 7% (95,600 t) of the total annual N flux and 13% (15,900 t) of the total annual P flux to the Gulf. Our SPARROW results include the losses in streams and reservoirs during downstream transport to the Gulf, which were estimated to be about 28% for P and 38% for N for WWTPs; therefore, it is estimated that 72% of the P and 62% of the N from WWTPs are transported to the Gulf. The delivery of nutrients from WWTPs was a little higher than overall nutrients because many WWTPs are found on larger rivers. Part of the difference in contributions from WWTPs found in this study from that estimated by the SAB may have been also caused by our total estimated inputs from WWTPs into the MARB (174,000 t of N and 16,300 t of P) being less than those used by the SAB (206,000 t for N and 38,200 t for P). Inputs of N and P from other commercial and industrial point sources, which were estimated to represent about 28% of the N and 23% of the P of all point sources (USEPA, 2007), were evaluated in SPARROW calibration but were not statistically significant; therefore, these source were not included in the models. These inputs were probably overestimated by the SAB because these sources usually withdraw water from streams with elevated N and P concentrations before being used and discharged back to the stream; therefore, part of the estimated N and P from these sources may have originated from other upstream sources. However, if commercial and industrial sources (N: 61,400 t estimated by the SAB and 62,600 t in this study; P: 14,800 by the SAB and 11,300 t in this study) were included with WWTPs effluent and delivered at the same rate as nutrients from WWTPs, total point source contributions to the Gulf would increase to 10% (N) and 19% (P), compared with 7% (N) and 13% (P) for WWTPs alone. Therefore, results of this study indicate that the importance of point sources of P (13–19%) is greater than that estimated in the other MARB studies, but much less than the upper limit described by the SAB (34%). In the MARB SPARROW P model, inputs from commercial and industrial point sources may be expected to be included in with WWTPs (and part of the reason why the WWTPs coefficient was greater than 1; 1.048 in Table 2) or with the urban and open areas source because most commercial and industrial sources are found in urban areas.

The inputs to the MARB SPARROW models represented inputs from WWTPs for 2002; however, some major WWTPs in the MARB have dramatically decreased their P inputs since 2002. For example, the Metropolitan Council Environmental Services Metro WWTP near St. Paul, MN, dramatically decreased P in their effluent (by about 90%) since 2002 (Heiskary and Wasley, 2010). Therefore, more recent (circa 2012) inputs from WWTPs may represent a little less of the total P load than that estimated with the MARB models.

Comparison of Modeling Techniques

Simple regression techniques, such as those described above for other studies of the MARB, may be good for describing the spatial distribution in concentrations, loads, and yields; however, results from simple regression relations may not accurately characterize cause-and-effect relations and often do not make physical sense, such as indicating that livestock manure, which was shown to be a very large source of P, is not important contributor in the MARB (Jacobson et al., 2011). Box and Draper (1987, p. 424) stated that "all models are wrong, but some are useful." It seems reasonable that the less wrong a model is, the more likely it is to be useful, but the question then becomes what makes a model "less wrong"? Besag (2002), a leading figure in spatial statistical analysis, stated, "I have always disliked the term 'statistical model' because I think it accords a status to formulations that is seldom earned in practice. . . . I prefer to reserve the term 'model' for something that has a physical justification." He went on to state that with respect to usual generalized linear models so popular in statistical analysis, he would prefer the term "scheme" or "prescription" to the term "model" to emphasize the lack of physical, or process, basis behind the model. This applies particularly to issues of causal inference and prediction, which Besag noted are closely related. So in Besag's sense, simple regression analyses such as those used by David et al. (2010), Jacobson et al. (2011), and Goolsby et al. (1999) are arguably not "models," and inferences regarding cause-and-affect, in contrast to simple association, should be regarded with a great deal of caution. In a similar vein, Box (1966) pointed out the dangers of assigning causal interpretations to regression coefficients, giving examples of how the failure to model the actual causal mechanisms can lead to inferences that are essentially the opposite of the truth with respect to causality in general or direction of action. For example, just because the coefficient for fixation in the Goolsby et al. (1999) study was zero or negative does not mean N fixed by legumes was completely removed from the watershed via harvesting or that its importance was minimal. Individual sources can act as surrogates for various other sources if they are correlated with one another (collinear); therefore, inputs that are correlated with one another may not be significant in a regression relation but still may be an important input. Such collinearity cannot be assessed by pairwise simple correlations and can arise from linear combinations of variables that show relatively low pairwise correlations. This could have occurred for crop fraction and manure in Jacobson et al.'s (2011) regression model, with the crop faction incorporating some of the effects of manure inputs and thus resulting in manure inputs being underrepresented and thus dismissed. In addition to these difficulties, if a sufficient number of sites are not monitored and thus included in the analysis, it is difficult to incorporate many explanatory variables into a regression relation. Therefore, results from simple statistical techniques, such as those previously used in the MARB, can result in misleading information on the importance of specific nutrient sources.

In contrast, SPARROW and other mechanistic models, such as SWAT and APEX, are based on underlying process models. Like all models, process-driven models involve some simplification and abstraction, but they should better represent the behavior of complex systems that simple linear description approaches may fail to capture, making them more trustworthy for prediction. Process models fall along a continuum of complexity, with tradeoffs between accurate representation of processes and ability to estimate a unique set of precise parameters. SWAT and APEX are highly parameterized mechanistic models that attempt to simulate all of the important processes occurring in the watershed. Each catchment can be provided with uniquely valued parameters that govern each of the numerous processes employed to explain contaminant fate and transport. Data covering large geographical areas, such as the MARB, are rarely available to estimate these catchment-specific parameters; parameters for almost all of the catchments are usually based on a very limited number of well monitored calibration sites. SPARROW is between the two extremes of simple regression equations and full process driven models. The spatially explicit, mass-balance, mechanistic framework of SPARROW enables individual nutrient sources to be tracked and quantified during downstream transport, assuming contributions from all of the sources are transported in a similar manner during downstream delivery. Mass contributions from measured sources are balanced with modeled losses to optimally match water quality at monitoring locations. The mechanistic mass-balance framework of SPARROW enables a relatively complete accounting of the nutrient sources, implying the overall delivery of these sources to monitoring locations in streams is reasonably estimated. However, the individual land-to-water delivery factors included in a final calibrated SPARROW model that affect this delivery may not represent all of the factors operating in an actual ecosystem, complicating the determination of their causative effect. Therefore, we caution the interpretation of each of the individual land-to-water delivery factors, similar to the caution that should be made when interpreting individual factors obtained with the simple regression approaches described above. It should be noted that although SPARROW, SWAT, and APEX are mechanistic models, it is still important to have monitoring sites describing a range in processes, sources, and environmental characteristics in the study area for model development.

Conclusions

SPARROW models were developed specifically for the MARB to improve the description of where and from what sources the N and P reaching the Gulf of Mexico originate. The MARB SPARROW models demonstrated that highest N and P yields were from catchments dominated by wastewater treatment plants, and that high delivered N yields were from catchments throughout the Middle Mississippi and Ohio River Basins, whereas high P yields were more widely distributed throughout the MARB. Agricultural inputs (manure, fertilizer, and legume crops) were the largest source of both N and P; however, farm fertilizers were the largest N source (41%), whereas manure and fertilizers were both important P sources (22 and 27%, respectively). MARB SPARROW models enabled better definition of agricultural and urban sources than in previous studies. This information can help managers prioritize the type of efforts to reduce nutrient loading to the Gulf of Mexico by understanding which sources are most important in various locations. By implementing the most appropriate actions in the most influential areas, it may be possible to reduce N and P loading from the MARB and thus reduce the size of the hypoxic zone in the Gulf of Mexico.

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