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Lake Nutrient Responses to Integrated Conservation Practices in an Agricultural Watershed

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Abstract

Watershed-scale management efforts to reduce nutrient loads and improve the conservation of lakes in agricultural watersheds require effective integration of a variety of agricultural conservation best management practices (BMPs). This paper documents watershed-scale assessments of the influence of multiple integrated BMPs on oxbow lake nutrient concentrations in a 625-ha watershed of intensive row-crop agricultural activity during a 14-yr monitoring period (1996–2009). A suite of BMPs within fields and at field edges throughout the watershed and enrollment of 87 ha into the Conservation Reserve Program (CRP) were implemented from 1995 to 2006. Total phosphorus (TP), soluble reactive phosphorus (SRP), ammonium, and nitrate were measured approximately biweekly from 1996 to 2009, and total nitrogen (TN) was measured from 2001 to 2009. Decreases in several lake nutrient concentrations occurred after BMP implementation. Reductions in TP lake concentrations were associated with vegetative buffers and rainfall. No consistent patterns of changes in TN or SRP lake concentrations were observed. Reductions in ammonium lake concentrations were associated with conservation tillage and CRP. Reductions in nitrate lake concentrations were associated with vegetative buffers. Watershed simulations conducted with the AnnAGNPS (Annualized Agricultural Non-Point Source) model with and without BMPs also show a clear reduction in TN and TP loads to the lake after the implementation of BMPs. These results provide direct evidence of how watershed-wide BMPs assist in reducing nutrient loading in aquatic ecosystems and promote a more viable and sustainable lake ecosystem.

Core Ideas

- We showed watershed-scale effects of integrated BMPs on lake nutrient concentrations.
- Decreases in several lake nutrient concentrations occurred after BMP implementation.
- Model simulations corroborated observed reductions in nutrient loads with BMPs.
- Results demonstrate watershed-wide BMPs reduce nutrient loading in aquatic systems.

Sustainable, environmentally responsible agricultural management is key to providing food, fiber, and, recently, biofuel production for a rapidly growing human population (US Census Bureau, 2012). The use of commercially produced fertilizers and manure has increased concomitantly, leading to potential ecological impacts both locally and far downstream of agricultural watersheds. Maintenance of freshwater water quality for viable fish and wildlife use, habitat resource, and other ecosystem services is fundamentally linked to both environmental and human health. A review by Naiman and Dudgeon (2011) detailed the critical importance of providing freshwater resources with sufficient quality to support a full range of ecosystem services that benefit society. It has been estimated that agriculture accounts for approximately 86% of the global freshwater use by humans (Hoekstra et al., 2011). Although nutrients are necessary for sustaining a viable ecosystem, elevated nutrient concentrations, primarily phosphorus (P) and nitrogen (N) from urban, agricultural, industrial, and municipal sewage sources, increase rates of eutrophication in receiving water bodies (Parris, 2011). The resulting eutrophication can directly lead to ecological and aesthetic degradation through significant increases in primary productivity via nuisance algal blooms (Parris, 2011; Renwick et al., 2008; Schindler et al., 2008), cascading through the system and potentially causing hypoxic conditions and contributing to ecologically unsustainable rivers, lakes, and streams (Parris, 2011).

Reports such as the US National Water Quality Inventory on surveyed lakes and rivers in the United States (USEPA, 2005) on the impacts of agricultural nonpoint-source pollution on water quality have underscored the need for concerted national efforts to preserve and enhance water resources. The USDA–ARS and the USDA–NRCS partnered in 2003 to implement an assessment of the effectiveness of NRCS conservation programs at watershed scales. The partnership, referred to as the Conservation Effects Assessment Project (CEAP), encompasses 14 watersheds across the United States to provide an empirical basis for this assessment at the watershed scale (Karlen, 2008). One of the selected CEAP watersheds was

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Abbreviations: AnnAGNPS, Annualized Agricultural Non-Point Source; BMP, best management practice; CART, classification and regression tree; CEAP, Conservation Effects Assessment Project; CRP, Conservation Reserve Program; CT, conservation tillage; FSR, forward stepwise regression; PRE, proportional reduction in error; SRP, soluble reactive phosphorus; TN, total nitrogen; TP, total phosphorus; VBS, vegetative buffer strip.

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Beasley Lake watershed, an agriculturally affected oxbow lake watershed located in the Lower Mississippi River Alluvial Plain in northwestern Mississippi (i.e., the Delta) (Locke et al., 2008). Agricultural production comprises approximately 36% of the Delta landscape, and many receiving water bodies in the region are under stress from sediments, nutrients, and pesticides (Brown and Froemke, 2012).

Beasley Lake was one of three watersheds evaluated from 1996 to 2003 as part of the Mississippi Delta Management Systems Evaluation Area project, an extension of the national Management Systems Evaluation Area effort in the midwestern United States (Locke, 2004; Onstad et al., 1991). An extensive water quality database on Mississippi Delta Management Systems Evaluation Area assessments through 2003 was published elsewhere (Cullum et al., 2006; Zablotowicz et al., 2006). Due to a 20-yr record of assessments, Beasley Lake watershed was recently incorporated as a Long-Term Agro-ecosystem Research Network watershed within the broader Lower Mississippi River Basin to assess agro-ecosystem sustainability through development and management of land use, environmental, and ecological datasets. Lizotte et al. (2014) reported on the impacts of watershed conservation practice on suspended sediment concentrations in Beasley Lake. The present study assesses the effectiveness of long-term watershed-wide integrated BMPs on lake P and N concentrations. The study's goals are to present the evolution of multiple, integrated combined BMP implementation within the Beasley Lake watershed and associated changes in lake water total P (TP), soluble reactive P (SRP), total N, ammonium-N (NH_4–N), and nitrate-N (NO_3–N) loads during a 14-yr monitoring period (1996–2009). This long-term database provides comprehensive empirical associations between watershed-wide multiple integrated combined BMPs and lake nutrients that are crucial to understanding lake water quality improvement and sustainability.

Materials and Methods

Watershed Site

Beasley Lake watershed is located in Sunflower County, MS (33°24′15″ N, 90°40′05″ W). Beasley Lake is an oxbow lake that is a historic meander cutoff from the adjacent Sunflower River (Fig. 1) that was isolated from the river channel at some time before 1940 (USGS, 2016). This shallow oxbow lake is a discontinuous polymictic lake with very weak short-term thermal stratification and moderate clinograde dissolved oxygen stratification during summer. Lake depth during the study period ranged from 1 to 3.4 m, with an average annual depth of between 2.1 and 2.4 m. The lake is vegetated primarily along the shorelines and littoral zone with alligator weed [*Alternananthera philoxeroides* (Mart.) Griseb.], duckweed (*Lemna* sp.), and bald cypress trees (*Taxodium distichum*) but is not dominated by aquatic vegetation at a nuisance level in the deeper limnetic-profundal zone (Scheffer, 2004). During summer, the lake is classified as eutrophic to hypereutrophic, with chlorophyll *a* concentrations frequently exceeding 25 μg L^{-1} (Dodds, 2002) and experiencing, on average, one major summer algal bloom per year. A 625-ha watershed provides the majority of surface drainage into the lake. The hydrologic drainage area of the watershed includes 150 ha composed of a nonarable riparian wetland containing a mixture of bottomland hardwood and herbaceous wetland vegetation and 339 ha composed of arable land that has been in row-crop production for four main crops throughout the 14-yr study period: cotton (*Gossypium hirsutum* L.), soybeans [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and milo [*Sorghum bicolor* (L.) Moench]. Beasley watershed consists

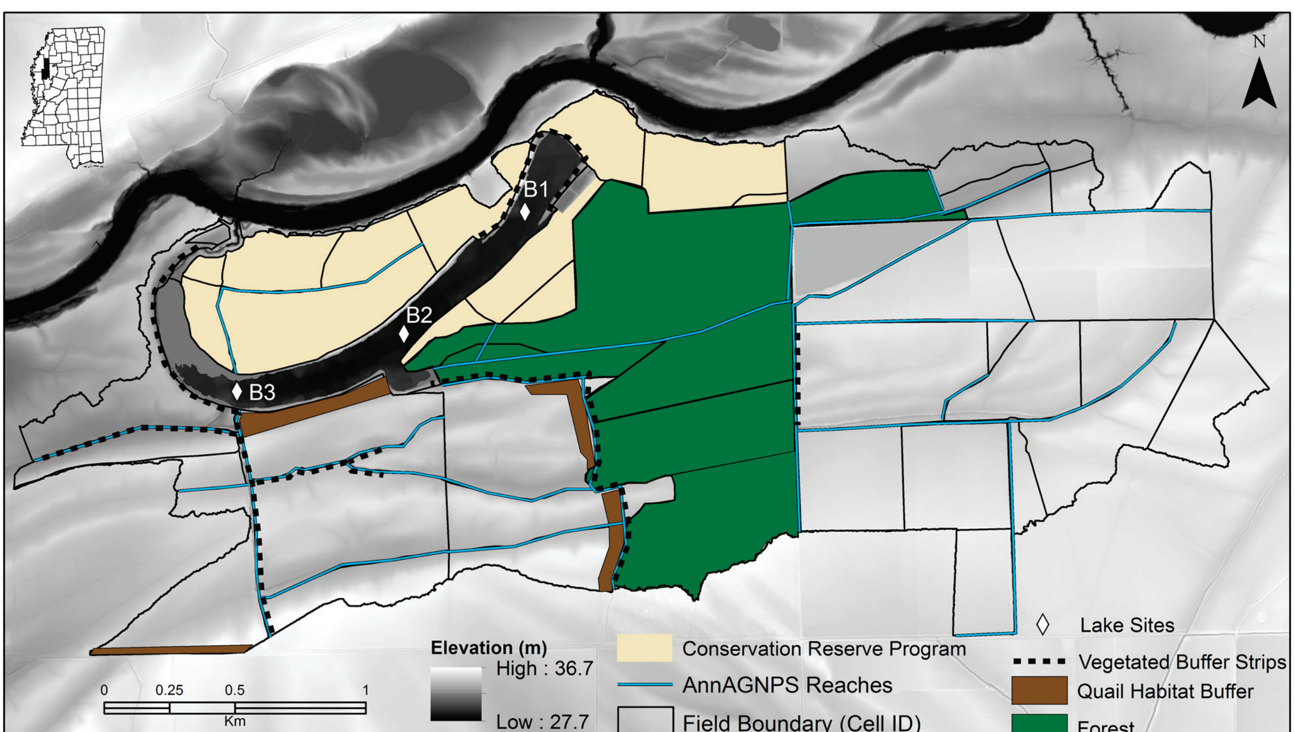


Fig. 1. Lidar remote sensing satellite image of Beasley Lake watershed with field boundaries and reaches as defined in the Annualized Agricultural Non-Point Source (AnnAGNPS) model, within-lake locations of nutrient sampling sites, and locations of the following best management practices: vegetated buffer strips, Conservation Reserve Program, and quail habitat buffer.

of a variety of soil types typical of floodplain soils adjacent to a meandering river. Major soil series represented include Alligator (very-fine, smectitic, thermic Chromic Dystraquerts), Bosket (fine-loamy, mixed, active, thermic Mollic Hapludalfs), Dowling (very-fine, smectitic, nonacid, thermic Vertic Epiaquepts), Dundee (fine-silty, mixed, active, thermic Typic Endoaqualfs), Forestdale (fine, smectitic, thermic Typic Endoaqualfs), and Sharkey (very-fine, smectitic, thermic Chromic Epiaquerts). Soil textures in these soil series range from sandy loam to clays. The lake surface area ranges from 25 to 30 ha, depending on runoff from the surrounding watershed. A culvert with a flap gate on a 1-m pipe at the western end of the lake (Fig. 1) serves as an outlet to the Sunflower River during periods when the lake level exceeds a stage of 29.6 m elevation. Average annual residence time for the lake is 87 d, with an average annual outflow flow rate of 0.0376 $m^3 s^{-1}$. Flow is intermittent during the year, with most outflow occurring during the wet season (December–June; i.e., winter and spring). During the dry season (July–November; i.e., summer and fall), outflow can be reduced to zero if there is no irrigation in the watershed and/or if there is no significant rainfall (>25.4 mm) for extended periods (weeks). Based on lake volume at high stage, maximum flow velocities in the lake are on the order of 2 $m^3 s^{-1}$, resulting in a representative residence time of approximately 6 d under high-flow conditions. The lake may also receive backwater from the Sunflower River through the western-most ditch (Fig. 1) at high river stage. Such backwater conditions are rare, occurring in 1999 and 2001 for 1 to 2 d.

Beasley Lake Watershed was first established as a research study site in 1995 with year-long nutrient monitoring beginning in 1996 as part of the Mississippi Delta Management Systems Evaluation Area to evaluate BMPs (Locke, 2004). After completion of the Mississippi Delta Management Systems Evaluation Area project, the watershed was selected as one of 14 USDA–ARS CEAP watersheds beginning in 2003 for continued long-term assessment of BMPs and in 2014 was incorporated as a research site into one of 18 broader (two-digit hydrologic unit code) long-term agroecosystem research watersheds.

From 1995 to 2009, four major independent BMPs, comprising >24.6% of the available arable land, were implemented. Beginning in 1995, the first structural edge-of-field BMPs were installed. One structural management practice included drainage culverts strategically located at low elevations within subdrainage areas (Rebich, 2004). Selected drainage pipes were modified with slotted board risers at the culvert inlet directly upstream from strategic sampling points. During fallow periods or when significant rainfall was anticipated, wooden boards were inserted into the slots to reduce the flow rate of runoff entering the pipe. Boards were then removed after settling of suspended sediment (Dabney et al., 2006). This BMP was not included in this analysis because the area of effect (in hectares) could not be reliably determined. The second structural edge-of-field BMP, vegetative buffer strips (VBSs) (NRCS practice 393, 601), initially encompassed 2.9 ha established along the west side of the lake prior to 1996 (Fig. 1). An additional 1.6 ha of VBS, implemented in 1995 to 1996, was composed of switchgrass (*Panicum virgatum* L.) or fescue (*Festuca arundinacea* Schreb.) (Locke et al., 2008). This was followed by a further addition of 4.6 ha of VBS composed of bahiagrass (*Paspalum notatum* Flugge) planted in 2001 (Fig. 1). These initial structural BMPs were implemented to inhibit suspended sediment and accompanying contaminant (e.g., fertilizers, pesticides) loads from entering the oxbow lake. Second, a cultural BMP was implemented beginning in winter 2001 to 2002: conservation tillage (CT) management (NRCS practice 329A, 329B) for cotton and soybeans, which encompassed varying arable portions of the watershed. From 2002 to 2004, in 2006, and from 2008 to 2009, CT soybeans were the primary row-crop (52–84% of arable land). The third major BMP in 2003 to 2004 involved implementing the Conservation Reserve Program (CRP) (NRCS practice 612), with 87 ha of arable land north of the lake being removed from row-crop production and planted in eastern cottonwood trees (*Populus deltoides* Bartr. Ex. Marsh.), oak trees (*Quercus* sp.), and hickory trees (*Carya* sp.) (Cullum et al., 2010; Locke et al., 2008) (Fig. 1). Approximately 0.9 ha of VBS north and east of the lake was subsumed into CRP at that time (Fig. 1). Also included within the CRP area was installation of a constructed wetland (NRCS practice 656) in 2003 (Locke et al., 2011). The fourth BMP was implemented in 2006 and comprised removal of 9 ha of arable land along the southern lake shoreline from row-crop production with conversion to vegetative buffer habitat to attract northern bobwhite quail (*Colinus virginianus*) (quail buffer habitat; NRCS practice 601) (Fig. 1).

Water Sample Collection and Analysis

Water quality samples were collected at three geo-referenced sites within Beasley Lake: Site 1, near the eastern end of the lake; Site 2, at lake mid-point; and Site 3, near the western end of the lake (Fig. 1). Biweekly lake water samples (1 L removed 5 cm from the water surface) were collected at each monitoring site from January 1996 through December 2009 (Cullum et al., 2010). Water samples were immediately chilled on wet ice (4°C) and transported to the USDA–ARS National Sedimentation Laboratory, Oxford, MS, for processing and nutrient analyses. Measured laboratory water quality parameters targeted for this study period were TP, SRP, NH_4–N, and NO_3–N. Total nitrogen (TN) data were not available until after 2000.

Methods used for analysis of water samples are described by Eaton et al. (2005). Briefly, TP was measured using the persulfate digestion method, and TN was assessed using the semi-micro Kjeldahl nitrogen method with the addition of measured NO_3–N and nitrite-N (as described below). Before analysis of the remaining nutrient analytes, sample water was filtered through a 45-μm cellulose nitrate filter. Soluble reactive P was measured using the ascorbic acid method. Ammonium-N was analyzed using the phenate method, and NO_3–N was determined according to the cadmium reduction method. Nitrite-N (used to help calculate TN) was measured using the diazotization method.

Data Analysis

To account for well-documented seasonal influence on shallow lake nutrient levels (Scheffer, 2004), nutrient data were sorted by year and site followed by the use of the 75th, 50th, and 25th percentiles to represent winter and spring, annual, and summer and fall conditions, respectively. Additionally, because water quality data are frequently non-normally distributed (Helsel, 1987; Yu et al., 1993), the percentile data were used as an indirect rank transformation allowing the data set to conform to the rule of normally distribution and thereby allowing for parametric statistical analyses (Conover and Iman, 1981). Several statistical methods were used to elucidate patterns of changes and assessment of integrated effects of implementation of multiple BMPs on lake nutrient responses. Classification and regression tree (CART) analysis using automatic interaction detection with the least squared loss method was conducted to assess change points or cut points (Haggard et al., 2013; Stevenson et al., 2012) when nutrient concentrations (dependent variable) changed, which conservation practice(s) (independent variable) was associated with that change, and the total implemented area(s) in hectares. Classification and regression tree analysis used percentile data to produce proportional reduction in error (PRE) and improvement values as goodness-of-fit statistics equivalent to multiple R^2 values. To account for variations in rainfall as a potential confounding variable, rainfall for the same percentiles as nutrients was included as a potential independent variable within the CART analysis. Stopping criteria for CART analysis proceeded with a minimum split index value of 0.05 and a minimum improvement in PRE of 0.05. The maximum number of nodes allowed was set at 21, with a minimum count of 5 allowed in each node. Forward stepwise regression (FSR) analysis was conducted to examine associations between changes in nutrients (dependent variable) and implemented area (in hectares) of four major BMP types and BMP locations (independent variables) over the 14-yr monitoring period (Lerch et al., 2015; Tuppad et al., 2010). Forward stepwise regression used percentile data to compute dimensionless standardized regression coefficients. Again, to account for variations in rainfall as a potential confounding variable, rainfall was included as a potential independent variable within the FSR. Analyses then proceeded by forcing rainfall into the equation and adding and removing variables using F to enter and remove values of 0.052 and 0.055, respectively. Statistical significance of the FSR, standardized regression coefficients, and R^2 values were reported at $p \leq 0.05$ (Lizotte et al., 2014).

AnnAGNPS Simulation Development

Annualized Agricultural Non-Point Source (AnnAGNPS) is a continuous, daily time step, pollutant loading model developed by the USDA–ARS and the NRCS to estimate watershed responses to agricultural management practices (Bingner et al., 2015). The model simulations in this study were generated using AnnAGNPS version 5.44a.003. Detailed information on AnnAGNPS model components and technical documentation can be found in Bingner et al. (2015).

AnnAGNPS requires inputs to describe the watershed topography, soil, management operations, and daily climate conditions. The inputs for the Beasley Lake watershed simulations were modified from an earlier study (Yuan et al., 2008) and were updated to reflect the most recent information available, including a new delineation of the watershed boundary determined with lidar topographic information (Fig. 1). Updated field areas, slopes, and dominant soil type as previously described were determined using ArcGIS. Soils data were updated to reflect the most current National Soil Information System soil profiles and associated parameters. Management inputs were developed to represent annual changes in land use and tillage practices at the field scale from 1996 to 2009. Generalized management schedules for each crop type (i.e., corn, soybean, cotton, and milo) were created to reflect typical practices over the 14-yr study period. Two alternative soybean management schedules were created to reflect the difference in CT and conventional tillage practices. The time of planting and fertilizer application rates were determined using an average value calculated from recorded data of actual practices during the study period.

Two model simulations were developed to examine the effect of BMPs on pollutant loads into Beasley Lake. One scenario represented implementation of cultural BMPs within the watershed, including the transition of 87 ha of cropland north of the lake to CRP beginning in 2003 and the implementation of reduced-till soybean in various fields after 2002. The second scenario represented watershed conditions without BMPs, including continuation of row-crop land use in the area north of the lake and a continuation of conventional tillage practices in all fields for all years. The two scenarios were compared to determine a percent difference in TN, TP, and TSS loads with and without BMPs. Structural BMPs, including VBS and drainage culverts, were not evaluated.

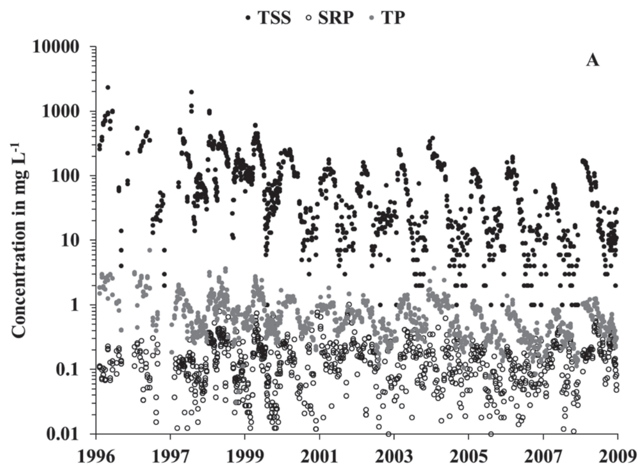
Results

Nutrient Lake Concentrations

Within the study oxbow lake, total and soluble P concentrations varied considerably from year to year within each season (Fig. 2A). Measured TP concentrations in the lake ranged from 0.10 (October 2008) to 3.90 mg L^{-1} (January 2005), with concentrations frequently exceeding 0.5 mg L^{-1}, often coinciding with high suspended sediment loads (Fig. 2A). From March through June, lake water TP concentrations were greatest from 1996 to 1998, when concentrations frequently exceeded 1 mg L^{-1} and sometimes exceeded 3 mg L^{-1}. Beasley lake water SRP concentrations during the 14-yr study period ranged considerably at all three sites from below detection limits (<0.01 mg L^{-1}) to >1 mg L^{-1} (October 2002). Most SRP concentrations, however, were between 0.01 and 0.2 mg L^{-1}. Measured TN lake concentrations ranged from 0.025 to >5 mg L^{-1} during 2001 to 2009 (Fig. 2B). Lake TN concentrations did not fluctuate much across years or months during the study period, with the exception of highs in July 2008 (5.18–7.02 mg L^{-1}) and lows in October to November 2006 (<0.1 mg L^{-1}). For dissolved inorganic N, measured NH_4–N concentrations ranged from <0.02 (below detection limit) to 0.99 mg L^{-1} during the study years, whereas NO_3–N concentrations ranged from <0.01 mg NO_3–N L^{-1} (below detection limits) to 6.49 mg NO_3–N L^{-1} with NO_3–N concentrations, occasionally exceeding 1 to 2 mg L^{-1} during winter and spring months (Fig. 2B).

Regression Models

Classification and regression tree analysis and FSR models of TP lake concentrations were produced for all percentiles (Tables 1 and 2). Total P CART analysis showed PRE values (similar to R^2 in regression models) ranging from 0.477 to 0.756 across percentiles (Table 1), with change points occurring in 1996 with rainfall and in 2002 with an additional 4.6 ha VBS in 2001. Forward stepwise regression analysis for TP produced R^2 values that were comparable to CART analysis, ranging from 0.494 to 0.536 across percentiles with negative slopes for VBSs and quail buffer habitat and positive slopes for rainfall (Table 2). These results indicated significant decreases in TP resulting from vegetated



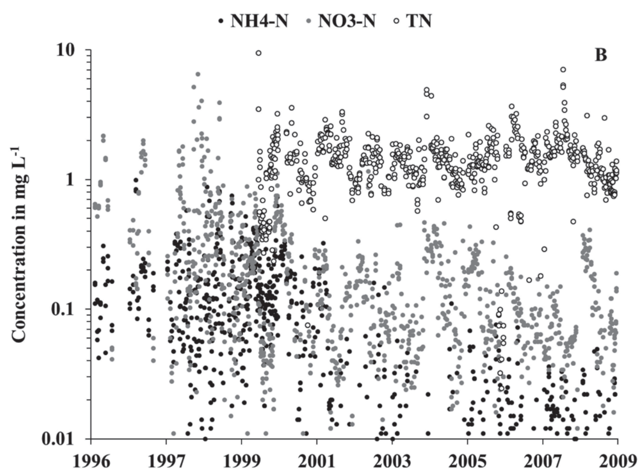


Fig. 2. Measured Beasley Lake biweekly surface water quality collected from three geo-referenced sites from January 1996 to December 2009 as (A) total suspended solids (TSS), total P (TP), and soluble reactive P (SRP) concentrations and (B) NH_4–N, NO_3–N, and total N (TN) concentrations in mg L^{-1}

BMPs. Soluble reactive P models from CART and regression analysis showed poor agreement among percentiles. For CART analysis, SRP PRE values ranged from 0.503 to 0.611 with multiple points. Rainfall and CT were the only consistent variables in all three models (Table 1). Forward stepwise regression analysis produced only one model for the 25th percentile and a modest R^2 value of 0.209 for rainfall (Table 2), indicating significant increases in SRP with concomitant increases in rainfall.

Nitrogen assessment produced a variety of models for TN, NH_4–N, and NO_3–N lake concentrations. For TN, several models included rainfall as the primary independent variable (Tables 1 and 2). Classification and regression tree TN percentile models showed change points with rainfall in 2001 and 2007 (75th, PRE = 0.799) and in 1996 and 2003 (50th, PRE = 0.604), whereas the 25th percentile changed with implementation of 87.3 ha CRP in 2003 and 163 ha CT in 2008. In contrast, TN FSR models showed limited agreement with CART, where only 50th percentile TN produced a significant model, indicating that TN decreased with increasing CRP area and rainfall (R^2 = 0.762). Ammonium analysis produced strong agreement among CART and FSR models across percentiles. Classification and regression tree models indicated NH_4–N percentile change points with CRP and CT areas (75th, PRE = 0.861; 50th, PRE = 0.761) as well as VBS area and rainfall (25th, PRE = 0.769) (Table 1). Similarly, FSR NH_4–N percentile models showed decreases after implementation of CRP, CT, and VBS, with R^2 values ranging from 0.612 to 0.839 (Table 2). Nitrate CART and FSR produced significant and consistent models where VBS was the primary independent variable. Classification and regression tree change points indicated that VBS area in 2002 and rainfall in 1996 influenced lake NO_3–N for nearly all percentiles (PRE range, 0.617–0.796) (Table 1). Forward stepwise regression models were nearly identical to CART and across all percentiles, showing a significant decrease in lake NO_3–N with increasing VBS area (Table 2).

AnnAGNPS Best Management Practice Simulation Results

AnnAGNPS simulations produced a comparison of the two scenarios with CRP and reduced tillage BMPs and without the respective BMPs that demonstrated a reduction in pollutant loads into the lake starting in 2003 and continuing through 2009, which was consistent with the timing of CRP implementation and reduced-till practices (Fig. 3 and 4). From 2003 to 2009, there was an average decrease of 29% in TN loads, 14% in TP loads, and 52% in TSS loads in the scenario with BMPs. AnnAGNPS model simulations showed very good agreement with CART and FSR models of dissolved inorganic N lake levels (NH_4–N and NO_3–N), limited agreement with TP CART and FSR models where change points and regressions coincided with VBS acreage in 2002, and less agreement with TN CART and FSR models, where CRP was a significant independent variable in only two models (Tables 1 and 2).

Discussion

Land-use changes comprising varying row-crop rotations with integrated implementation of the four major BMP types within the watershed significantly influenced Beasley Lake P concentrations over the 14-yr study period (Table 2; Fig. 2). Reduction of nutrient influx into lentic water bodies such as oxbow lakes is a major challenge to restoration efforts of impaired lakes (Carpenter and Lathrop, 1999; Jeppesen et al., 2007; Lijklema, 1994). One of the most challenging nutrients to control is P (Jeppesen et al., 2007; Nixdorf and Deneke, 1997; Schindler et al., 2008). Despite the significant decreases in TP concentrations in Beasley Lake, P concentrations are still greater than those in comparable Mississippi Alluvial Plain oxbow lakes described by Justus (2010) as least impaired, where median TP ranged from 0.034 to 0.242 mg L^{-1}. As a result, efforts such as placement of additional BMPs should continue to try to further reduce TP loads to improve Beasley Lake water quality. Responses of lake water SRP to implemented and integrated BMPs were not consistently evident (Tables 1 and 2), and efforts to reduce SRP in Beasley Lake are much more challenging for several reasons. First, in some instances in the Mississippi Delta CT practices have been reported to increase soluble P in runoff as a result of remaining crop residues (Schreiber et al., 2001). Second, challenges of continuing lake internal P loading from previous influxes of soil-bound P occurring in lake sediments can significantly influence SRP levels (Jeppesen et al., 2007; Meals et al., 2010; Zaccara et al., 2007). Third, even if all influxes of external P into the lake are abated, internal loading of P can create a significant lag time in SRP responses, on the order of decades (Meals et al., 2010).

Observed N concentrations in Beasley Lake water before implementation of CT practices and additional BMPs (Table 2; Fig. 2B) were comparable to those in other agriculturally affected oxbow lakes (Cullum et al., 2006; Zablotowicz et al., 2010). Beasley Lake water NH_4–N concentrations after these BMPs were implemented (Fig. 2B) were comparable with oxbow lakes described as least impaired, with concentrations typically ranging from 0.015 to 0.048 mg NH_4–N L^{-1} (Justus, 2010).

Nitrate-nitrogen is often the predominant soluble inorganic N species in surface waters with sufficient dissolved oxygen (Dodds, 2002). In the current study, winter (January–March) surface water NO_3–N appeared to be minimally affected by BMPs within the watershed. In contrast, NO_3–N concentrations during spring months (April–June) exhibited clear trends and significantly decreased across years after implementation of multiple BMPs. Schreiber et al. (2001) observed that soluble N species, such as NH_4–N and NO_3–N, in runoff can be substantially reduced when CT practices are implemented. Furthermore, additional decreases in soluble N can occur when arable land is vegetated during winter and spring with cover crops (Schreiber et al., 2001) or conversion to CRP where vegetative cover occurs year-round (Cullum et al., 2010). This vegetation allows for a greater potential of N uptake and/or immobilization of these more labile N species. Concentrations of NO_3–N during summer (July–September) and fall months (October–December), although much lower than winter and spring concentrations, exhibited less consistent decreases in concentrations across years after implementation of any BMPs in the Beasley Lake watershed. Measured NO_3–N concentrations reported in the current study across all months were comparable with those of other studies in oxbow lakes in the region (Cullum et al., 2006; Justus, 2010; Zablotowicz et al., 2010). Peak winter and spring monthly

Table 1. Classification and regression tree analysis for nutrients (dependent variable) and conservation practices or rainfall (independent variable) at the 75th, 50th, and 25th percentiles of water quality data in Beasley Lake from 1996 to 2009 with model cut point (where the independent variable separates the dependent variable into groups), proportional reduction in error (PRE) values (model goodness-of-fit), and improvement values (individual independent variable goodness-of-fit)

Nutrient† (percentile)	Node	Mean	SD	Conservation practice or rainfall				
				Variable‡	Cut point	Year	PRE	Improvement
SRP (75th)	1	0.20	0.06	rain	121 cm	1999	0.276	0.276
	2	0.16	0.03	VBS	8.82 ha	2002	0.328	0.052
	3	0.22	0.05	CT	78 ha	1999	0.469	0.141
	7	0.23	0.05	CT	119 ha	2004	0.548	0.080
	9	0.22	0.04	rain	150 cm	2008	0.611	0.063
TP (75th)	1	1.16	0.61	VBS	8.82 ha	2002	0.477	0.477
NH_4–N (75th)	1	0.09	0.09	CRP	87.3 ha	2003	0.786	0.786
	2	0.16	0.06	CT	111 ha	1996	0.861	0.075
NO_3–N (75th)	1	0.37	0.35	VBS	8.82 ha	2002	0.617	0.617
TN (75th)	1	1.70	0.28	rain	174 cm	2001	0.302	0.302
	2	1.78	0.25	rain	144 cm	2007	0.799	0.497
SRP (50th)	1	0.13	0.05	CT	78 ha	1997	0.123	0.123
	3	0.09	0.02	CT	111 ha	1996	0.442	0.319
	5	0.12	0.04	CT	255 ha	2001	0.550	0.109
TP (50th)	1	0.76	0.46	VBS	8.82 ha	2002	0.397	0.397
	2	1.14	0.56	rain	72 cm	1996	0.516	0.225
NH_4–N (50th)	1	0.05	0.06	CRP	87.3 ha	2003	0.650	0.650
	2	0.10	0.05	CT	113 ha	1998	0.761	0.321
NO_3–N (50th)	1	0.18	0.16	VBS	8.82 ha	2002	0.589	0.589
	2	0.34	0.17	rain	72 cm	1996	0.721	0.132
TN (50th)	1	1.38	0.23	rain	93 cm	2003	0.604	0.604
SRP (25th)	1	0.06	0.04	CT	78 ha	1997	0.165	0.165
	3	0.07	0.04	rain	45 cm	1998	0.442	0.277
	5	0.06	0.03	CRP	87.3 ha	2003	0.503	0.061
(25th) TP	1	0.49	0.27	VBS	8.82 ha	2002	0.427	0.427
	2	0.72	0.32	rain	48 cm	1996	0.756	0.329
	3	0.36	0.1	rain	74 cm	2002	0.812	0.056
NH_4–N (25th)	1	0.03	0.04	VBS	8.82 ha	2002	0.601	0.601
	2	0.07	0.04	rain	48 cm	1996	0.769	0.167
NO_3–N (25th)	1	0.10	0.13	VBS	8.82 ha	2002	0.336	0.336
	2	0.20	0.17	rain	48 cm	1996	0.796	0.460
TN (25th)	1	1.12	0.23	CT	163 ha	2008	0.172	0.172
	3	1.04	0.13	CRP	87.3 ha	2003	0.234	0.061

† SRP, soluble reactive phosphorus; TN, total nitrogen; TP, total phosphorus.

‡ CRP, Conservation Reserve Program; CT, conservation tillage; VBS, vegetative buffer strip.

Table 2. Forward stepwise regression analysis of nutrients: soluble reactive P (SRP), total P (TP), ammonium-N (NH_4–N), nitrate-N (NO_3–N), and total N (TN) vs. conservation practices: vegetative buffer strips (VBS), conservation reserve program (CRP), quail buffer habitat (QB), and rainfall at the 75th, 50th, and 25th percentiles of water quality data in Beasley Lake from 1996 to 2009.†

Percentile	*n*	Nutrient	Standardized regression coefficients					R^2	*p* value	Equation
			VBS	CRP	CT	QB	Rain			
75th	42	SRP					0.478	0.209	0.001	SRP = 0.0706 + (0.000952 × RAIN)
	42	TP	**−0.569**			−0.255		0.497	<0.001	TP = 2.440 − (0.162 × VBS) − (0.0379 × QB)
	42	NH_4–N		**−0.944**	−0.247			0.839	<0.001	NH_4–N = 0.200 − (0.00183 × CRP) − (0.000274 × CT)
	42	NO_3–N	**−0.782**					0.603	<0.001	NO_3–N = 1.295 − (0.127 × VBS)
	27	TN						none		
50th	42	SRP						none		
	42	TP	**−0.800**				0.443	0.536	<0.001	TP = 1.106 − (0.169 × VBS) + (0.0101 × RAIN)
	42	NH_4–N	**−0.532**	−0.446			0.276	0.746	<0.001	NH_4–N = 0.111 − (0.0146 × VBS) − (0.000597 × CRP) + (0.000814 × RAIN)
	42	NO_3–N	**−0.766**					0.577	<0.001	NO_3–N = 0.587 − (0.0562 × VBS)
	27	TN		−0.461			**−0.966**	0.762	<0.001	TN = 2.839 − (0.00290 × CRP) − (0.0134 × RAIN)
25th	42	SRP						none		
	42	TP	**−0.854**				0.371	0.494	<0.001	TP = 0.956 − (0.106 × VBS) + (0.00514 × RAIN)
	42	NH_4–N	**−0.909**				0.264	0.612	<0.001	NH_4–N = 0.119 − (0.0173 × VBS) + (0.000560 × RAIN)
	42	NO_3–N	**−0.582**					0.322	<0.001	NO_3–N = 0.348 − (0.0339 × VBS)
	27	TN						none		

† Values in bold indicate the independent variable with the largest standardized coefficient for each regression, blank cells indicate independent variables excluded from stepwise regression due to lack of significance, and "none" indicates no significance among any independent variables assessed.

Beasley Lake water NO_3–N concentrations, ranging from 0.61 to 1.19 mg L^{-1} before implementation of multiple BMPs, were similar to other Mississippi Delta oxbow lakes with intensive row crop agriculture in the watershed (Cullum et al., 2006). In comparison, spring and summer monthly Beasley Lake water NO_3–N concentrations ranging from 0.01 to 0.16 mg L^{-1} after implementation of multiple BMPs were closer to those occurring in the least affected oxbow lakes of the Mississippi Alluvial Plain (Justus, 2010). Although BMPs reduced dissolved inorganic N concentrations (i.e., NH_4–N, NO_3–N), some studies showed that attempts to control eutrophication in shallow lakes via N mitigation alone would be insufficient (Nixdorf and Deneke, 1997; Schindler et al., 2008). Best management practices, such as those implemented in the current study, that combine reductions in both P and N inputs to lake surface water would have

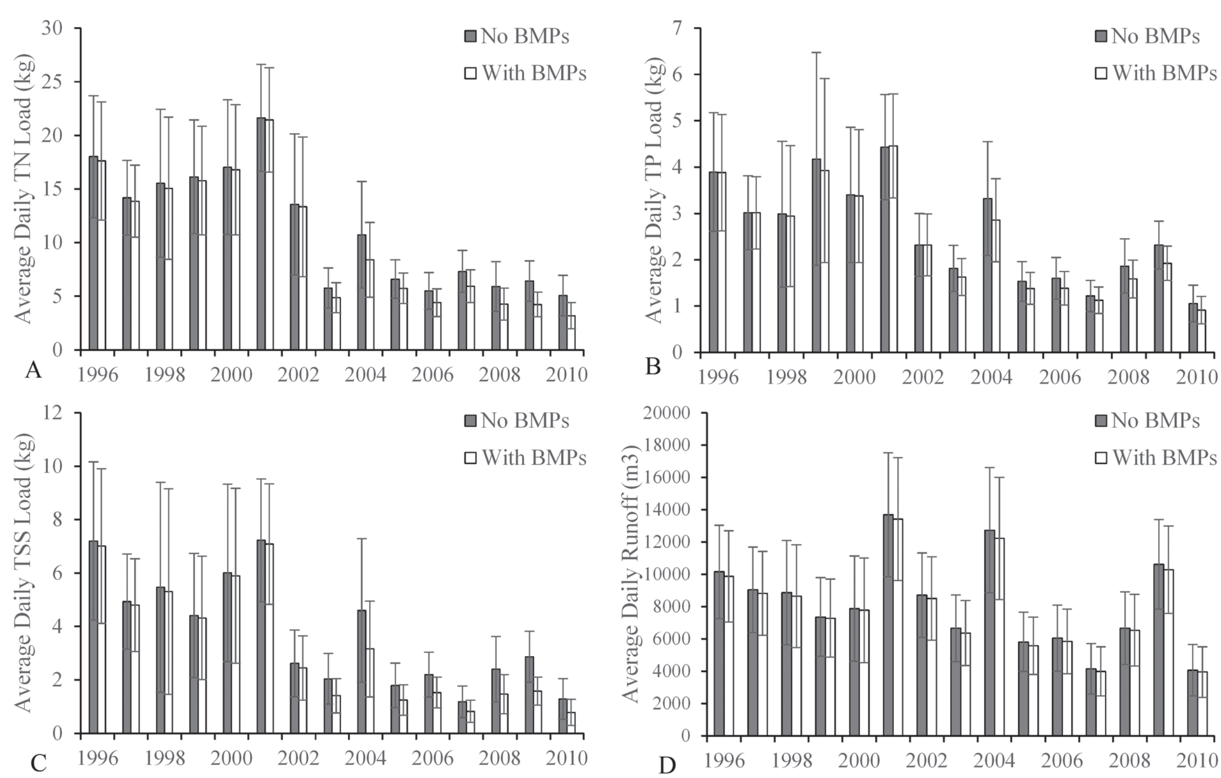


Fig. 3. Annualized Agricultural Non-Point Source (AnnAGNPS) model-simulated annual average daily (A) total N (TN), (B) total P (TP), (C) total suspended solids (TSS), and (D) runoff loads into Beasley Lake with and without watershed Best Management Practices (BMPs) (including reduced-till soybean and Conservation Reserve Program) in Beasley Lake watershed from 1996 to 2009.

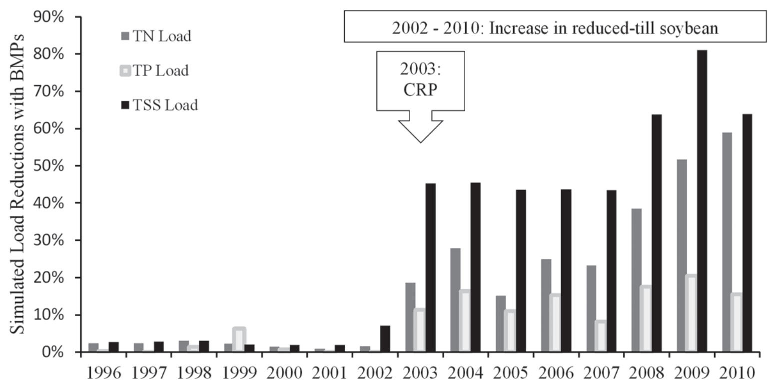


Fig. 4. Annualized Agricultural Non-Point Source (AnnAGNPS) model simulated total N (TN), total P (TP), and total suspended solids (TSS) percent load reductions with implementation of Conservation Reserve Program (CRP) and reduced till soybean Best Management Practices in Beasley Lake watershed from 1996 to 2009.

the best chance for success and are a significant step toward lake rehabilitation.

Production of regression models is an important tool in watershed management and can be used to enhance current point-source water quality models such as AnnAGNPS (Tomer et al., 2013; Yuan et al., 2008). Regression models produced from long-term, watershed-scale data bases allow for more refined assessments of the effects of combined BMPs at the watershed scale and improved water quality models. This is one of the many critical goals of the national CEAP assessment (Locke et al., 2008; Tomer and Locke, 2011).

Watershed-scale, longer-term (>10 yr) studies such as this study are necessary to improve our understanding of how agriculturally affected shallow lakes can be rehabilitated and sustained using multiple combined agricultural BMPs (Carpenter and Lathrop, 1999). Several previous studies have quantified the mitigation of nutrients in agricultural runoff using a specific type of BMP, such as vegetative filter strips (Blanco-Canqui et al., 2004a, 2004b; Rao et al., 2009), reduced tillage practices (Schreiber et al., 2001), and conservation reserve practices (Cullum et al., 2010), at smaller, field-plot scales. Other studies have tried to assess the long-term effects of combined BMPs on P, but with only a limited variety of BMPs (e.g., multiple storm water detention ponds) (Daroub et al., 2009). Fewer still are the studies that have attempted to assess nutrient reduction via BMPs at a watershed scale (Cullum et al., 2006; Locke et al., 2008; Makarewicz et al., 2009; Yuan et al., 2013; Zablotowicz et al., 2006).

The present study showed significant long-term improvement in lake surface water quality. Reductions in most nutrient parameters coincided with cumulative combined implementation of a variety of BMPs. These included structural localized edge-of-field practices in 1996, 2001, and 2006 to watershed-wide cultural practices such as CT in 2001 and watershed-wide structural practices such as CRP in 2003. Underlying all the implemented agricultural BMPs is the goal to reduce pollutant loadings into the lake. The focus is primarily to reduce topsoil erosion during runoff events from agricultural land and concomitant transport of nutrients, such as soil-bound P and dissolved inorganic N (Schreiber et al., 2001; Yuan et al., 2008, 2013). Failure to reduce these loads can lead to a degraded trophic state within the lake because excessive nutrient levels induce nuisance algal blooms. As a result, reductions in TP and dissolved inorganic N concentrations within Beasley Lake surface water due to integrated implementation of multiple BMPs within the watershed could mitigate algal blooms, increase water clarity, and improve trophic conditions, leading to lake rehabilitation and sustainability.

Lake water quality concentrations and AnnAGNPS loads cannot be compared directly because a lake model is necessary to represent the processes occurring within the lake, such as the deposition of sediment and sediment-bound nutrients, resuspension of sediment and organic matter, biological utilization and release of nutrients, and denitrification (Chao et al., 2010). In addition, AnnAGNPS results do not reflect the implementation of VBSs and drainage culverts, and therefore the results cannot confirm the benefits of these conservation practices. However, the timing of load reductions simulated with AnnAGNPS corroborate the observed water quality trends seen in the lake, including a decrease in TP and NH_4 occurring after 2002 (Fig. 2 and 3).

Summary and Conclusions

The current study provided an increased understanding of the effects of agricultural BMPs in mitigating nutrient loads into Beasley Lake and improving water quality. In addition, our study improved the capability of predicting nutrient changes in lake water quality in conjunction with watershed-wide changes in land-use patterns. Watershed-wide multiple agricultural BMPs implemented over the course of the 14-yr study period reduced TP and soluble N primarily during spring months (April–June) and to a lesser extent during summer months (July–September). Beasley Lake spring monthly TP decreased across years after implementation of VBSs (1996 and 2001), CT (2001–2002), CRP (2003–2004), and quail habitat buffer (2006) BMPs. Beasley Lake spring monthly NH_4–N decreased across years after implementation of CT (2001–2002), followed by implementation of CRP (2003–2004) BMPs until reaching near or below lowest detection limits. Lake spring NO_3–N decreased after implementation of VBSs (1996 and 2001), CT (2001–2002), and CRP (2003–2004) BMPs, but this decrease did not continue thereafter. In every instance, when monthly rainfall was a significant independent variable, the associated nutrient concentration increased. Watershed modeling with AnnAGNPS estimated a decrease in N and P loads into the lake from 2003 to 2009 after implementation of CRP and reduced tillage, which concur with observed trends in reductions in spring TP, spring NH_4–N, and late-spring NO_3–N in lake concentrations. Through combined analysis of long-term observed lake water quality and watershed modeling, this research provides critical evidence for the effectiveness of agricultural BMPs in maintaining a healthy, sustainable lake ecosystem.

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