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RESEARCH ARTICLE

Effects of a forested state park on stream nutrient concentrations in an agriculturally dominated watershed in the U.S. Midwest

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Abstract

Agricultural land cover in the U.S. Midwest is a major source of nutrient pollution that has led to impairment of stream water quality. This study examines the impact of a forested state park on nutrient concentrations within an agriculturally dominated watershed. Water samples were collected over a 2-year study period from eight stream sampling sites along four creeks and processed for total nitrogen (TN), nitrate (NO_3^--N), total phosphorus (TP), and orthophosphate (PO_4^{3-}-P). Hydrology, channel morphology, and remotely sensed land cover and vegetation data were also collected and analyzed within the study area. Results indicate that water quality responses to a forested state park vary between TN, NO_3^--N, TP, and PO_4^{3-}-P, and water quality variables are uniquely influenced by watershed and stream characteristics. The greatest water quality benefits most frequently occurred within the two smallest study streams with the greatest residence times and proportion of watershed areas within the forested state park. Overall, the greatest improvements to water quality occurred during periods of low stream discharge and when riparian vegetation was greenest. The results of this study suggest that conservation of forested areas within agriculturally dominated watersheds can provide water quality improvements in the U.S. Midwest. Targeting watersheds that drain small streams with long residence times for conservation may be most beneficial to improving water quality.

KEYWORDS
nutrients, water quality, land cover, hydrology, geomorphology

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Research Impact Statement

Conservation of forested areas in the U.S. Midwest can be effective in reducing stream nutrient concentrations within agriculturally dominated watersheds.

1 | INTRODUCTION

Anthropogenic impacts on freshwater environments are a major concern for states that comprise the Great Lakes region of the U.S. Midwest, especially as agricultural production continues to lead to severe water quality degradation (Falcone et al., 2018; Giri & Qiu, 2016; Renwick et al., 2018). Nonpoint source pollutants, including from cropland runoff, are widespread across U.S. Midwestern landscapes, making them difficult to track and regulate (Mello et al., 2018). Excessive nutrient inputs can result in eutrophication, which can lead to increased algal growth, anoxic zones, and the release of toxins (Carpenter et al., 1998; Dodds & Smith, 2016). Prior to colonization and widespread anthropogenic land conversion of the U.S. Midwest and subsequent declines in water quality, these landscapes primarily consisted of forests or grasslands. Remaining undeveloped land areas within agriculturally dominated watersheds may result in nutrient reductions within stream environments.

Many previous studies have shown the important role that land use has on stream nutrient dynamics. Generally, agricultural land cover is associated with higher phosphorus and nitrogen concentrations and loads (Carpenter et al., 1998; Nielsen et al., 2012; Ostrofsky et al., 2018). Forest cover and riparian zones, in contrast, have been shown to improve water quality through phosphorus and nitrogen removal (Lefebvre et al., 2005; Lowrance et al., 1997; Ostrofsky et al., 2018; Peterjohn & Correll, 1984; Webber et al., 2003; Weigelhofer et al., 2018). Furthermore, forest cover is one of the most important land cover types to preserve water quality in low order streams (Mello et al., 2018). However, due to extensive forest loss throughout the agricultural U.S. Midwest, most previous studies are limited to a focus on the effects of relatively thin riparian buffer strips (e.g., almost always <100 m and often <20 m) rather than more substantial forested areas (Bosompemaa et al., 2021; Lee et al., 2004). Larger forested areas may be more effective at removing nutrients as small riparian buffers are often ineffective at improving water quality in agricultural watersheds (e.g., Grudzinski et al., 2020).

In some areas, hydrogeological setting within a riparian zone may have a more significant impact on water quality than riparian buffer properties (Hill, 2017; Vidon & Smith, 2007). Fluctuations of hydrological characteristics may also drive changes in stream nutrient levels. For example, increases in precipitation and surface runoff can increase stream discharge and groundwater exchange rates (Arntzen et al., 2006; Shrestha & Kazama, 2007; Vega et al., 1998). Nutrient flux from the watershed can also increase as streamflow increases from higher rates of overland flow during storm events (Petry et al., 2002). Sediment mobilization from runoff may release additional sediment-bound nutrients particularly phosphorus into the water column (Wallbrink et al., 2003). High flows decrease water residence time in fluvial systems due to increased water velocity (Rech et al., 2018; Withers & Jarvie, 2008), while nutrient uptake by vegetation and stream algae can increase during periods of low flow and high water residence time (Bernot et al., 2006; Chen et al., 2010; Jansson et al., 1994; Royer et al., 2004). In the U.S. Midwest, land cover and stream hydrology may have variable impacts on nutrient concentrations. For example, in one study, both agricultural land cover and stormflow discharge were found to be significant drivers of total nitrogen (TN), orthophosphate (PO_4^{3-} - P), and total phosphorus (TP) concentrations, but stormflow discharge was not a significant driver of nitrate (NO_3^- - N) concentrations (Lazar et al., 2019). Nitrate concentrations may be more heavily influenced by streamflow associated with seasonal changes rather than storm pulses (Kalkhoff et al., 2016). Phosphorus concentrations may also remain more consistent than nitrogen concentrations through seasonal changes in streamflow but have been shown to be more sensitive to larger storm events (Kalkhoff et al., 2016; Vanni et al., 2001). Therefore, peaks in phosphorus input may be higher during months with the greatest precipitation.

In addition to land use and stream hydrology, seasonal changes in vegetation cover can also influence water quality (Griffith et al., 2002). Within a forested riparian buffer, vegetation condition or "greenness" is often quantified using the Normalized Difference Vegetation Index (NDVI), derived from satellite remote sensing. Vegetation growth, photosynthetic capacity, and greenness are typically highly correlated with NDVI (Griffith et al., 2002; Robinson et al., 2017; Zhu et al., 2015). NDVI has previously been shown to be more correlated with water quality parameters than actual land cover and land use (Griffith et al., 2002). Early growing season NDVI, which is also referred to as the onset of greenness, can be a strong predictor of water quality parameters (Griffith et al., 2002). Previous studies in regions with seasonality have found sub-basin NDVI to be a significant factor in predicting nonpoint source nutrient loading (Oki & Yasuoka, 2008; Ouyang et al., 2009). Additionally, the utilization of riparian buffers with high NDVI adjacent to farmlands was found to be an effective management strategy for reducing nonpoint source nutrients (Ouyang et al., 2009). Increased TN and TP input in the spring and summer can also increase hydrophyte growth and consequently increase vegetation index values as well as nutrient uptake (Chen et al., 2010; Zhu et al., 2015).

Channel morphology and stream size may also impact stream nutrient dynamics. Larger streams have a higher water volume to creek bed ratio than smaller streams (Alexander et al., 2000; Royer et al., 2004). This relationship results in less nitrogen and phosphorus exchange with the creek bed and therefore, potentially, a decreased reduction in nutrients within the water column (Alexander et al., 2000; Bernot & Dodds, 2005; Withers & Jarvie, 2008). Low order streams are also expected to have a shallower depth, which increases light penetration. With increased light penetration primary production rates and nutrient uptake may increase (Withers & Jarvie, 2008). Increased channel complexity and sinuosity can also increase flow paths, hyporheic exchange, transient storage, and residence time (Covino, 2017; Roley et al., 2012). Streams with a more complex morphology may yield the highest denitrification rates (Alexander et al., 2000; Bernot & Dodds, 2005; Opdyke et al., 2006). Studies have shown that riffles with coarse sediment may have lower denitrification rates than storage zones such as pools with finer sediment, higher organic matter concentrations, and increased residence time (Hill et al., 1998; Opdyke et al., 2006). Pools may also provide short term retention of phosphorus due to sorption by sediment, while long term retention may be a result of biological uptake; however, retention is limited by transport during storm events and high flows (Meals et al., 1999; Withers & Jarvie, 2008). Therefore, channel morphology may have less of an influence on phosphorus retention in comparison to hydrology and biochemical processes associated with phosphorus uptake (Bernot & Dodds, 2005; Withers & Jarvie, 2008).

Currently, research that examines how various stream types (e.g., size, morphology, and hydrology) can impact water quality within preserved temperate forested parks located in otherwise agricultural watersheds is lacking. Additionally, studies that examine nutrient removal within forested streams are largely based on short term nutrient additions which can alter natural nutrient uptake processes. Thus, the primary goal of this study was to determine if a forested landscape, contained within a state park, can provide water quality improvements within an agriculturally dominated watershed in southwest Ohio. The secondary goal of this study was to identify additional factors that may influence spatial changes (upstream vs. downstream) in nutrient concentrations within a forested area.

1.1 | Primary research question

Does a forested state park impact nitrogen and phosphorus concentrations in an agriculturally dominated watershed in Southwest Ohio?

Hypothesis I. All nutrient concentrations (TN, NO_3^--N, TP, PO_4^{3-}-P) will decrease within the forested state park.

1.2 | Secondary research question

Do discharge, vegetation condition (NDVI), or stream characteristics impact changes in nutrient concentrations within the forested state park?

Hypothesis I. An increase in discharge and lower water residence time will result in a decrease in nutrient reduction within the state park due to lower potential for nutrient uptake, nutrient deposition, and denitrification.

Hypothesis II. An increase in NDVI will be associated with a greater decrease in all nutrient concentrations due to increased uptake by vegetation.

2 | METHODS

2.1 | Study area

This study was completed within the Four Mile Creek Watershed, which is located on the border of Southwest Ohio and Southeast Indiana, U.S., and is part of the greater Great Miami River watershed (Figure 1; Figure S1). The four creeks sampled for water quality were Four Mile Creek, Little Four Mile Creek, Marshall's Branch, and Deer's Ear (Deer's Ear is an unofficial colloquial name). All four study creeks drain into the northern portion of Acton Lake, within Hueston Woods State Park. Each creek had two sampling locations: one located at the northern park boundary of the state park with farmland and another located downstream within the state park prior to each of the creeks flowing into Acton Lake or where lake water backs up into a creek from the lake and thus flow ceases (Figure 1). The watershed is dominated by corn and soybean production, but a variety of sustainable agricultural practices have been put in place to manage nutrient and sediment runoff (Kelly et al., 2019; Renwick et al., 2018; Figure S1). Despite these efforts, the creeks and lake within the watershed remain subject to eutrophication.

The geologic units present within the study area include Ordovician bedrock, glacial till, and glacial outwash. The bedrock is mostly lithified limestone or unlithified shale and is mostly overlain by Wisconsin glacial till. Creeks primarily consist of step-pool and pool-riffle geomorphology (Rech et al., 2018), however, the creeks have variable underlying geology, including median creek bed sediment particle size, bedrock exposure, and overall channel morphology (Table 1). Four Mile Creek has the largest total watershed drainage area and average channel area,

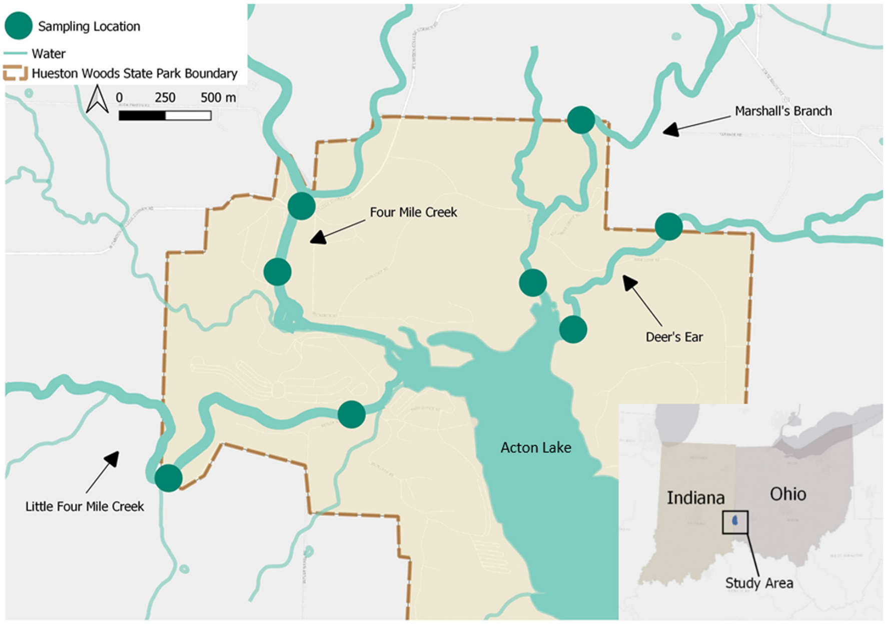

FIGURE 1 Sampling was completed on the four main creeks that drain into Acton Lake: Four Mile Creek, Little Four Mile Creek, Marshall's Branch, and Deer's Ear. Each creek had a sampling location at the park boundary and a point downstream before water enters the lake or where the lake seasonally backs up into the stream channel during periods of high lake levels.

TABLE 1 The total drainage basin area (km^2) was measured in ArcGIS Pro 2.7.2 following watershed delineation. The discharge (m^3/s) and pool volume (m^3) were measured in the field during baseflow conditions during October 2020. Residence time (RT) is a function of discharge (*Q*) and pool volume (*V*) and is calculated as $RT = V/Q$. The average channel width and depth were also measured in the field during baseflow conditions in December 2020. The average channel area (m^2) was calculated by multiplying each cross section width by average depth. Creek bed sediment surveys were completed in October 2020 utilizing a Wolman pebble count.

Watershed characteristics and stream morphology				
Parameter	**Four Mile Creek**	**Little Four Mile Creek**	**Marshall's Branch**	**Deer's Ear**
Total drainage basin area (km^2)	134.36	83.60	14.33	10.88
Percent of basin area within park (%)	0.39	0.62	9.91	5.71
Total pool volume in study area (m^3)	1198.40	1033.50	908.27	347.12
Discharge (m^3/s)	0.51	0.28	0.047	0.051
Baseflow RT (min)	39.54	64.09	323.41	113.19
Distance between sampling points (m)	398.72	1361.80	1180.36	975.16
Average width (m)	18.36	17.48	12.25	9.09
Average depth (m)	0.62	0.63	0.48	0.42
Average channel area (m^2)	11.43	11.06	6.08	4.20
Average width: depth	29.50	27.63	27.03	23.36
D-16 (mm) creek bed particle size	4.85	45.00	22.50	16.00
D-50 (mm) creek bed particle size	22.50	128.00	60.00	60.00
D-84 (mm) creek bed particle size	128.00	Bedrock	128.00	90.00

followed by Little Four Mile Creek, Marshall's Branch, and Deer's Ear. Marshall's Branch and Deer's Ear have the largest proportion of their overall watershed areas within the forested state park (Table 1). Four Mile Creek is the widest, while Marshall's Branch is the deepest creek within the state park. Four Mile Creek and Little Four Mile Creek have the highest amount of pool volume within the state park and Marshall's Branch has the longest residence time (Table 1).

In the study area, the wettest months of the year are generally March through July. As temperature reaches its peak at the end of July and into August, the precipitation begins to decrease. The driest months are August through October and February (Debrewer et al., 2000; Rech et al., 2018). Summer and spring precipitation events tend to be shorter and more intense than those in fall and winter (Debrewer et al., 2000).

The highest discharges in the creeks are typically observed in March and April and the lowest discharges are typically observed from August to October. During the study period, stream discharge followed typical seasonal patterns for the study area and storm events occurred across all seasons (Figure 2).

2.2 | Data collection and analysis

2.2.1 | Water sampling

There were a total of eight creek surface sampling points (Figure 1), with two surface sampling points on each creek (Four Mile Creek, Little Four Mile Creek, Marshall's Branch, and Deer's Ear). Water samples were collected approximately every 2 weeks from December 2019 to December 2021 with the exception of a pause from March 8, 2020, to May 22, 2020, due to the beginning of the COVID-19 pandemic along with August 18, 2020–November 3, 2020, and September 19, 2021–October 24, 2021, due to regular seasonal drying. Additional opportunistic sampling was also completed following occasional storm events (Figure 2). Following the initial COVID-19 lockdown, several weekly samples were collected to account for the pause in sampling. Samples were collected in 4 L bottles and kept on ice until sampling was completed. A total of 46 sampling days occurred throughout the study period. Water samples were stored in a temperature-controlled room at 4°C until processing.

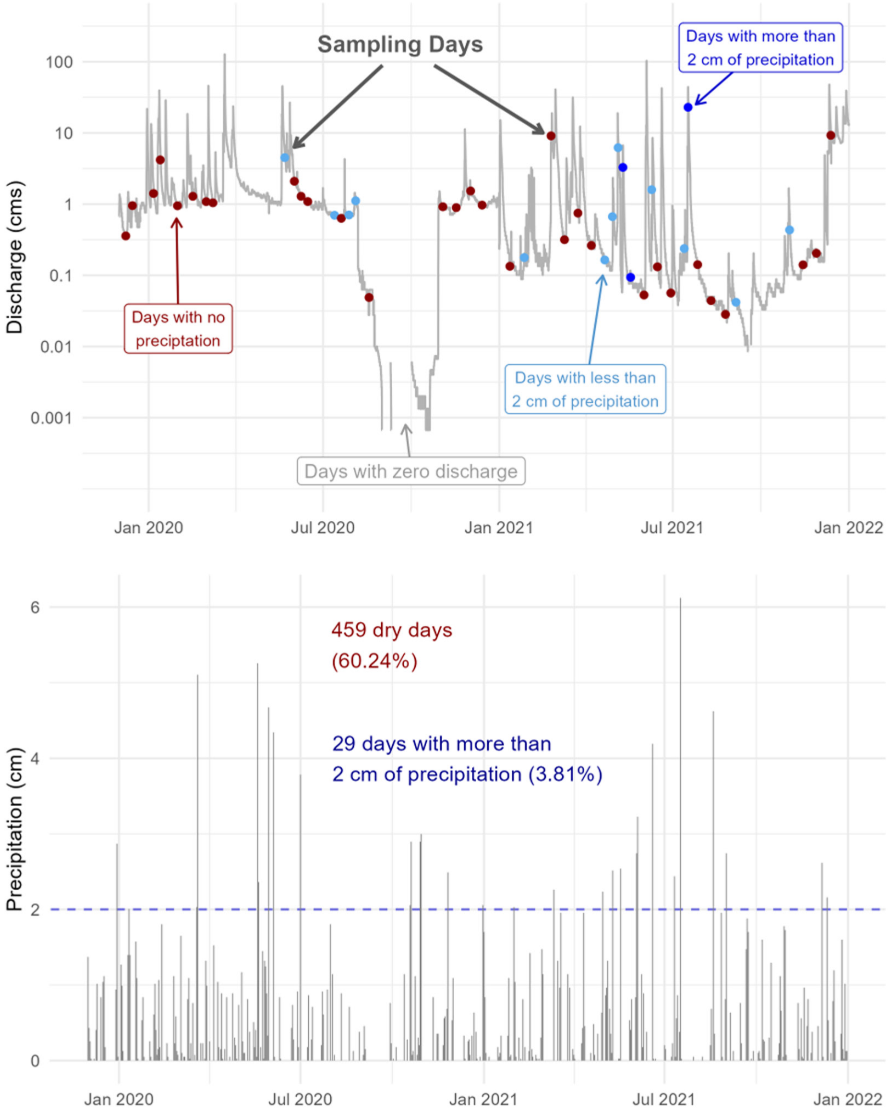

FIGURE 2 Hydrograph for Four Mile Creek with sampling days (top) and precipitation throughout the study period (bottom).

2.2.2 | Nutrient analysis

All samples were processed within 48 h of collection. The water samples were processed for TN, TP, NO_3^- - N, and PO_4^{3-} - P. From each water sample, one 125 mL sub-sample was filtered using a type a/e glass microfiber filter to isolate NO_3^- - N and PO_4^{3-} - P present in the sample. All samples were acidified with 188 μL of sulfuric acid for preservation until analysis. Nitrate was measured using the cadmium reduction method (QuikChem® 10-107-04-1-A), and PO_4^{3-} - P was measured using the molybdate blue method (QuikChem® 10-115-01-1-Q). An unfiltered TN and TP subsample was analyzed following a manual persulfate digestion to convert all the nitrogen and phosphorus into NO_3^- - N and PO_4^{3-} - P, respectively. The concentrations of the digested subsamples were then measured using the aforementioned methodology for NO_3^- - N and PO_4^{3-} - P analyses. All nutrient analyses were completed using a Lachat QuikChem® 8500 Series II nutrient analyzer.

2.2.3 | Hydrological and morphological data

Stream stage (m) was recorded using Onset HOBO® automatic water level loggers, which were installed on Four Mile Creek, Little Four Mile Creek, and Marshall's Branch within monitoring wells. Stages were converted to discharges with previously created stage-discharge rating curves for the study area (Kelly et al., 2019; Renwick et al., 2018). For statistical modeling, the stage-discharge value that corresponded with the time of sampling was utilized. The discharge in Deer's Ear, which is ungauged, was scaled by the relative watershed area of Marshall's Branch. Marshall's Branch and Deer's Ear are adjacent to one another and are similar in size and thus have similar discharge characteristics. Water samples were collected during a wide range of hydrologic conditions ranging from 100% baseflow to >99% runoff. In general, low discharge periods contained the highest fractions of baseflow.

Total pool volume (m^3) was calculated within the park between the upstream and downstream sampling points for the four study creeks during baseflow by summing the volume of individual pools. Pool volume was calculated by multiplying the average length (m), width (m), and depth (m) of each pool within a creek. These morphological parameters were collected using a stadia rod (pool depth) and a reel tape measure (width and length). During the same day, discharge was measured on each creek to calculate residence time. Residence time (min) was calculated as pool volume (m^3)/stream discharge (m^3/s). Riffles were not included in the residence time calculation as the amount of time that water is located within a riffle in the study area is negligible (always <1 min and often less than 10 s per riffle, based on visual observation). It is important to note that residence time will vary within each creek under various flow conditions. However, relative residence time will remain consistent between streams. Streams were at a moderate baseflow when residence time was calculated for this study. Discharge was measured in the field using the velocity-area method. For the velocity-area method, velocity and area were measured within each creek using a Flow Tracker 2 Acoustic Doppler Velocimeter (ADV®) (Herschy, 1998).

Morphological measurements were also taken at cross sections on each creek between sampling points. On Little Four Mile Creek, Marshall's Branch, and Deer's Ear, a minimum of 10 equidistant cross sections were established, while four cross sections were established on Four Mile Creek due to the shorter distance between upstream and downstream sampling sites and consistent channel morphology. Bankfull width (m) was measured from the top of the lower bank to the equivalent elevation on the opposite bank. Depth (m) measurements were taken along the bankfull width and averaged. The W:D was calculated by dividing the channel width by the average depth. The average channel area (m) was calculated by multiplying the width by the average depth for each cross section. All width, depth, W:D, and channel area measurements were then averaged by each creek (Grudzinski & Daniels, 2018; Harrelson et al., 1994). A Wolman pebble count was completed using a gravelometer to compare creek bed particle size among the different creeks (Wolman, 1954). One hundred substrate samples were measured (mm along the b-axis) at each cross section within the four creeks. The median D-16 (16th percentile), D-50 (median), and D-84 (84th percentile) particle sizes (mm) for each creek were calculated following the Wolman pebble count method (Grudzinski & Daniels, 2018; Olson et al., 2005).

2.2.4 | Remote sensing

Vegetation conditions were quantified using the NDVI derived from 10 m Sentinel-2 imagery. Image processing was completed within the Google Earth Engine (GEE) cloud computing platform (Gorelick et al., 2017). NDVI was calculated using red and near-infrared (NIR) wavelengths: (NIR − Red)/(NIR + Red) (Reed et al., 1994). Ten-day composites surrounding water sampling dates (five before and five after) were used to determine vegetation conditions during sampling events and to limit effects of cloud coverage. One-hundred-meter buffer zones were created around the creeks in QGIS v. 3.16.1 (QGIS Development Team, 2009). We selected a 100 m buffer width due to relatively narrow floodplains and decreased likelihood of vegetation outside of the 100 m distance to have direct interactions with water within the stream channel (e.g., due to root network extension), while also providing an adequate sample size of 10 m Sentinel-2 pixels to capture vegetation and not just water and the stream channels. Mean NDVI was calculated within the buffer zones between the boundary sampling point and the most downstream in-park sampling point using the zonal statistics plugin within QGIS v. 3.16.1.

2.2.5 | Data analysis

All statistical modeling was completed in R v. 4.3.2. A pre-post analysis of covariance (ANCOVA) was used to model the nutrient reduction within the park (i.e., park effect); essentially a convolution of linear regression and analysis of variance (ANOVA). This technique can best be understood by considering the equation of a simpler pre-post regression model:

$$Y_{\text{post}} = \beta_0 + \beta_1 Y_{\text{pre}} + \beta_2 \text{Disharge} + \beta_3 \text{NDVI}.$$

Here, the “post” nutrient concentration is the downstream sample within the park (see Figure 1), which is a function of the “pre” nutrient concentration sampled at the park boundary where each creek enters from farmland. The effects of discharge and NDVI are also incorporated into the model. The “ANOVA” part of the approach allows each β-coefficient to vary by creek (a unique β_i for each of the four creeks). A pre-post ANCOVA is recommended by the United States Environmental Protection Agency (USEPA) to assess changes in water quality as the result of a treatment in a paired-watershed study design (United States Environmental Protection Agency, 2016). Numerous studies have utilized this approach to model upstream versus downstream water quality changes (e.g., Bishop et al., 2005; Grabow et al., 1999; Uwimana et al., 2017).

As a visual analysis, nutrient reductions (mg/L) were calculated as the downstream concentrations minus the upstream concentrations. Thus, a negative value indicates a water quality improvement. To statistically assess the impact of the forested state park on nutrient concentrations, a regression coefficient *t*-test was used to determine if the nutrient concentrations at each downstream sampling point were significantly less than the upstream sample concentrations (Cressie & Whitford, 1986), by testing if the β_1 coefficient is less than unity. To test for a global park effect in this study, the change in concentration coefficient β_1 was independent of the different creeks (i.e., a single β_1 coefficient is in the model, instead of one for each creek). After testing for a global park effect, Akaike information criterion, Bayesian information criterion, and adjusted R^2 values were used to build a more parsimonious model (Burnham & Anderson, 2004; Johnson & Omland, 2004) which all suggested that the park effect differed within each creek (all suggest a unique β_1 for each of the four creeks). Confidence intervals were calculated from the fitted model to examine the influence of the park, discharge, and NDVI within each creek (Bishop et al., 2005; Chaffin et al., 2018; Nielsen et al., 2012), where an interval on the park coefficient is significant if it is below the value unity, and discharge and NDVI effects on the downstream measures are significant if the interval does not include zero. A Bonferroni multiple comparisons correction was used to mitigate type I error from building multiple intervals (Armstrong, 2014). Channel morphology characteristics were not included in the statistical models as the number of creeks would not allow for robust analyses on the impact of these variables. Residual analysis was performed to assess model assumptions and test for the presence of autocorrelation (Fisher & Gallagher, 2012). We found the residuals from the fitted ANCOVA models were approximately normally distributed and uncorrelated.

3 | RESULTS

3.1 | Total nitrogen

Concentrations of TN over the study period ranged from 0.21 to 11.58 mg/L. Raw upstream and downstream TN concentrations for each study stream are shown within Figure S2. The ANCOVA and regression coefficient *t*-test suggest that there was not an overall park effect for TN reduction ($p = 0.073$). However, the tests indicated that the impact of the park, the impact of discharge, and the impact of NDVI on TN concentrations varied by creek ($p < 0.001$, $p = 0.037$, and $p < 0.001$, respectively; Table 2; Table S1).

The confidence intervals derived from the model showed that the park significantly reduced TN concentrations within Marshall's Branch (CI: 0.74, 0.93, Figure 3a; Table 2). The park did not have a significant impact on TN concentrations within Four Mile Creek, Little Four Mile Creek, or Deer's Ear. Within Marshall's Branch TN experienced the greatest downstream reductions during low discharges (CI: 0.023, 2.78; Figure S3). There were no statistically significant relationships between discharge and TN reductions within Four Mile Creek, Little Four Mile Creek, or Deer's Ear. Within Marshall's Branch TN experienced the greatest downstream reductions during periods of high NDVI (CI: −2.54, −1.05; Figure S4). No significant relationship was detected between NDVI and TN reduction within Four Mile Creek, Little Four Mile Creek, or Deer's Ear.

TABLE 2 Model summary statistics of park effect for each of the four creeks. The $\hat{\beta}$ values correspond to regression coefficients in the analysis of covariance models—the proportional reduction in nutrient level. 95% confidence intervals were built with a Bonferroni correction within each nutrient type. Values less than 1 correspond to a reduction in nutrient level (a significant park effect). Significant responses are highlighted in bold.

	$\hat{\beta}$	$SE_{\hat{\beta}}$	CI: lower limit	CI: upper limit
TN				
Four Mile Creek	1.03	0.027	0.96	1.10
Little Four Mile Creek	0.99	0.020	0.94	1.04
Marshall's Branch	**0.83**	**0.038**	**0.74**	**0.93**
Deer's Ear	0.98	0.037	0.89	1.07
NO_3^- - N				
Four Mile Creek	1.01	0.018	0.97	1.06
Little Four Mile Creek	1.00	0.013	0.96	1.03
Marshall's Branch	**0.90**	**0.025**	**0.84**	**0.96**
Deer's Ear	**0.94**	**0.024**	**0.88**	**1.00**
TP				
Four Mile Creek	0.99	0.067	0.82	1.16
Little Four Mile Creek	**0.78**	**0.046**	**0.66**	**0.90**
Marshall's Branch	**0.50**	**0.047**	**0.39**	**0.62**
Deer's Ear	0.87	0.12	0.55	1.18
PO_4^{3-} - P				
Four Mile Creek	1.06	0.0601	0.91	1.21
Little Four Mile Creek	0.97	0.0710	0.79	1.15
Marshall's Branch	**0.43**	**0.0498**	**0.30**	**0.55**
Deer's Ear	**−0.0031**	**0.0473**	**−0.12**	**0.12**

3.2 | Nitrate

Concentrations of NO_3^- - N over the study period ranged from 0.019 to 11.60 mg/L. Raw upstream and downstream NO_3^- - N concentrations for each study stream are shown within Figure S5. The ANCOVA and regression coefficient *t*-test suggests that there was an overall park effect for NO_3^- - N reduction ($p = 0.016$). The ANCOVA model indicated that the influence of the park, the impact of discharge, and the impact of NDVI on NO_3^- - N concentrations varied by creek ($p < 0.001$, $p = 0.005$, $p < 0.001$, respectively; Table 2; Table S1).

The park significantly reduced NO_3^- - N within Marshall's Branch and Deer's Ear (CI: 0.84, 0.96; 0.88, 1.00, respectively; Figure 3b; Table 2). Within Four Mile Creek and Marshall's Branch NO_3^- - N experienced the greatest downstream reductions during low discharges (CI: 0.021, 0.073; 0.084, 0.71, respectively; Figure S6). However, these relationships were largely driven by one sample point during a high flow event. There was no statistically significant relationship detected between discharge and NO_3^- - N within Little Four Mile Creek or Deer's Ear. Within Marshall's Branch NO_3^- - N experienced the greatest downstream reductions during periods of high NDVI (CI: −1.89, −0.86; Figure S7). No significant relationship was detected between NDVI and NO_3^- - N within Four Mile Creek, Little Four Mile Creek, or Deer's Ear.

3.3 | Total phosphorus

Concentrations of TP over the study period ranged from 0.0080 to 0.42 mg/L. Raw upstream and downstream TP concentrations for each study stream are shown within Figure S8. The ANCOVA and regression coefficient *t*-test suggests that there was an overall park effect for TP reduction ($p < 0.001$). The results of the ANCOVA indicated that the impact of the park, the impact of discharge, and the impact of NDVI on TP concentrations varied by creek ($p < 0.001$, $p < 0.001$, $p = 0.003$, respectively; Table 2; Table S1).

The confidence intervals derived from the model showed that the park significantly reduced TP concentrations within Little Four Mile Creek and Marshall's Branch (CI: 0.66, 0.90; 0.39, 0.62, respectively; Figure 3c; Table 2). Within Little Four Mile Creek and Marshall's Branch, TP experienced the greatest downstream reductions during low discharges (CI: 0.0005, 0.015; 0.12, 0.27, respectively; Figure S9). There were no statistically significant relationships detected between TP and discharge within Four Mile Creek or Deer's Ear. Within Marshall's Branch TP

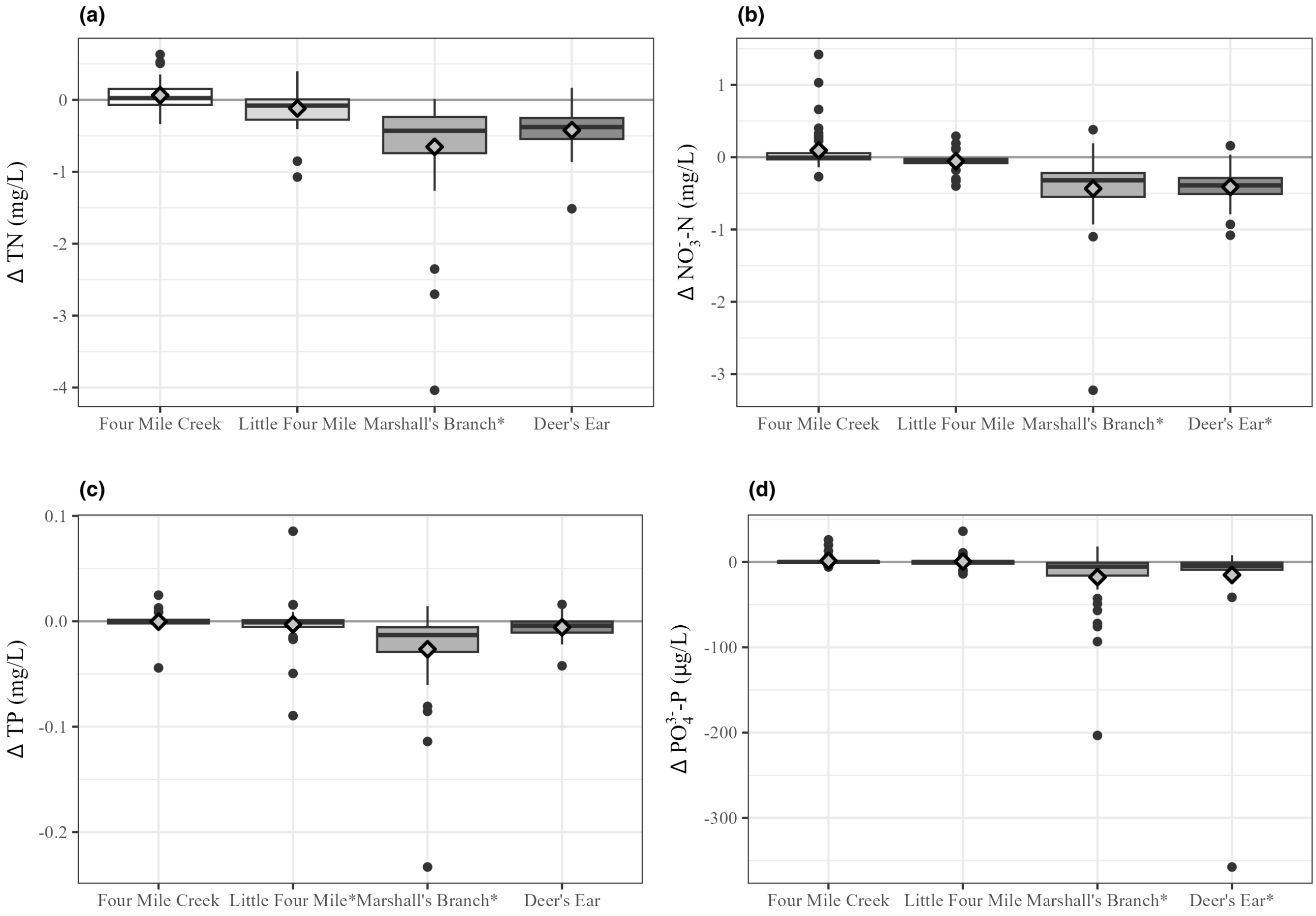

FIGURE 3 Changes in total nitrogen (TN) (a), nitrate (NO_3^- - N) (b), total phosphorus (TP) (c), and orthophosphate (PO_4^{3-} - P) (d) concentration (mg/L) between study creeks. The "*" indicates a statistically significant reduction within a certain creek.

experienced the greatest downstream reductions during periods of high NDVI (CI: −0.088, −0.020). No significant relationship was detected between NDVI and TP in Four Mile Creek, Little Four Mile Creek, or Deer's Ear (Figure S10).

3.4 | Orthophosphate

Concentrations of PO_4^{3-} - P over the study period ranged from 3.36 to 377 μg/L. Raw upstream and downstream PO_4^{3-} - P concentrations for each study stream are shown within Figure S11. The ANCOVA and regression coefficient *t*-test suggests that there was an overall park effect for PO_4^{3-} - P reduction ($p < 0.001$). The results of the ANCOVA indicated that the influence of the park, the influence of discharge, and the influence of NDVI on PO_4^{3-} - P concentrations varied by creek ($p < 0.001$, $p < 0.001$, $p = 0.002$, respectively; Table 2; Table S1).

The confidence intervals derived from the model showed that the park significantly reduced PO_4^{3-} - P concentrations within Marshall's Branch and Deer's Ear (CI: 0.30, 0.55; −0.12, 0.12, respectively; Figure 3d; Table 2). Within Marshall's Branch and Deer's Ear PO_4^{3-} - P experienced the greatest downstream reductions during low discharges (CI: 34.48, 73.89; 74.33, 131.27, respectively; Figure S12). However, these relationships were largely driven by one sample point during a high flow event. There were no statistically significant relationships detected between discharge and PO_4^{3-} - P reduction within Four Mile Creek or Little Four Mile Creek. Within Marshall's Branch PO_4^{3-} - P experienced the greatest downstream reductions during periods of high NDVI (CI: −77.87, −17.29). There was no significant relationship between NDVI and change in PO_4^{3-} - P concentration within Four Mile Creek, Little Four Mile Creek, or Deer's Ear (Figure S13).

4 | DISCUSSION

The findings of this study demonstrated that a forested state park can improve water quality by reducing nutrient concentrations within agriculturally dominated U.S. Midwestern watersheds. These findings are consistent with other studies that have shown reductions in nutrients from riparian buffers within agricultural watersheds (Lowrance et al., 1984; Peterjohn & Correll, 1984), yet unique as they reveal the effects of a larger forested area and the importance of stream characteristics. The results of the statistical models that examined the influence of the park were primarily driven by reductions in TN, NO_3^--N, TP, and PO_4^{3-}-P within the two smallest study creeks (Marshall's Branch and Deer's Ear). The modest nutrient reductions resulting from the forested state park within the smaller creeks are likely related to morphological and hydrological characteristics of these creeks along with a greater portion of the overall watershed areas being located within the forested state park (Table 1). For example, Marshall's Branch had nearly 10% of its watershed area within the forested state park, had the longest distance between sampling points, and exhibited consistent improvement across all water quality parameters. Deer's Ear had the second highest frequency in improved water quality parameters and had over 5% of its overall watershed area within the state park. Meanwhile, Four Mile Creek and Little Four Mile Creek each had <1% of their watershed areas within the forested state park and only TP within Little Four Mile Creek showed a statistically significant improvement (Tables 1 and 2). Little Four Mile Creek which had the longest distance between sampling points, did not show consistent improvements in water quality, indicating that a large stream distance between sampling points does not by itself drive improvements in water quality. Smaller streams also exhibit a smaller water volume to stream bed surface area ratio compared to larger streams, which increases the potential for benthic exchange and nutrient removal (Alexander et al., 2000; Bernot & Dodds, 2005; Withers & Jarvie, 2008). Additionally, as stream size increases, denitrification has been shown to be a less significant mechanism for reductions in nitrogen loads (Bernot & Dodds, 2005). Furthermore, Marshall's Branch and Deer's Ear have the highest water residence times which provides even more opportunity for nutrients to settle or be taken up by biota (Hill et al., 1998; Meals et al., 1999; Opdyke et al., 2006; Withers & Jarvie, 2008). Overall, during our study period, the greatest improvements in water quality occurred during warmer months (May–August). Warmer periods may be more conducive to improving water quality as streams move through forested areas, due to increased chemical processing, including through instream denitrification and riparian uptake. However, it is important to note that seasonal changes in water quality may vary year to year due to differences in hydrologic and weather conditions. Additionally, in our study, seasonal patterns and changes in water quality were not always consistent across all streams.

It was expected that changes in nutrient concentrations would be impacted by stream discharge (Covino, 2017; Kalkhoff et al., 2016; Kelly et al., 2019; Lazar et al., 2019; Wallbrink et al., 2003). Discharge was found to be predictive of changes in all nutrient concentrations within Marshall's Branch and also for NO_3^--N within Four Mile Creek, TP within Little Four Mile Creek, and PO_4^{3-}-P within Deer's Ear. Due to potentially variable nutrient spiraling lengths, additional forested area and thus longer forested stream lengths may be needed to reduce nutrient concentrations within larger creeks (Covino, 2017; Doyle, 2005; Ensign & Doyle, 2006). Legacy nutrient deposits within the watershed can also complicate the relationship between discharge and nutrient concentrations by releasing buried nutrients into the water column (Kreiling et al., 2019; Kusmer et al., 2018; Van Meter et al., 2018; Weigelhofer et al., 2018).

NDVI was found to be predictive of nutrient reductions only within Marshall's Branch, which also has the greatest residence time (Table 1). Increased residence time may allow for more efficient nutrient withdrawal via riparian vegetation and denitrification. There are complex relationships with phosphorus and nitrogen limitation in aquatic ecosystems that examining was outside the scope of this study. For example, algal and fish communities can have a significant influence on nutrient concentrations in freshwater environments (Andersen et al., 2019; Bernot et al., 2006; Dodds et al., 2002; Hamilton et al., 2001). Additionally, vegetation can also reach saturation points, which reduces nutrient uptake capacity (Bernot et al., 2006; Finkler et al., 2018; Schade et al., 2010). Future studies that quantify nutrient transfer from streams into riparian vegetation across seasons within geomorphologically heterogenous streams would be highly informative.

This study helps to fill a research gap pertaining to the influence of a forested state park on nutrient concentrations within an agriculturally dominated watershed, while taking anthropogenic and natural drivers of water quality into consideration. The results of the study demonstrate the importance of natural area protection and where preservation efforts could be prioritized. The findings of this study suggest that a forested state park can be effective at reducing nutrient concentrations in fluvial environments that drain agricultural land. Results indicate that 5%–10% of watershed area may need to be forested to consistently improve water quality. Our results also indicate that without increased proportions of watersheds (e.g., >10%) within forested land cover, water quality improvements may remain limited in agricultural landscapes. Additionally, this study highlights the importance of stream morphology when considering which stream characteristics to include in conservation areas if water quality improvements are a goal. Small order streams with a high residence time showed the greatest improvements in water quality. However, studies outside of this park (and biome) are needed to determine if results from this study are consistent within other areas.

One of the limitations of this study is the limited size of the state park (~3000 acres or 1200 ha). We encourage future studies to examine larger protected areas to determine how watershed and stream size within a forested area may impact water quality. If larger forested areas are found to be needed to improve water quality in larger streams (e.g., such as Four Mile Creek), a significant investment may be needed to convert greater land areas from agricultural land use to forested land cover. If larger areas are not available for conservation purposes, conserving smaller forested streams with longer residence times may show the greatest benefit for water quality.

Long-term studies may provide additional insights into trends associated with nutrient concentrations, discharge, and NDVI that may have been limited by a 2-year study period. Although nutrient concentrations were generally reduced within the forested park, it is currently unknown how far downstream the modest nutrient reductions are retained once water drains out of the forested area and back through farmland. The results of this study could also vary within different regions of the United States that have adopted different agricultural practices and exhibit different climates, soils, vegetation patterns, and land use histories.

5 | CONCLUSION

Based on the results of this study, conservation of forested areas within agriculturally dominated watersheds can have a positive impact on water quality in the U.S. Midwest. The results of this study were primarily driven by nutrient reductions within the smaller streams in this forested state park. Substantial investments may be needed to conserve adequate watershed areas for water quality to improve, particularly in larger stream networks. Discharge was a driving factor for changes in nutrient concentrations but impacts varied by site and water quality parameters. The larger residence times in smaller creeks appear to be beneficial at the scale of this study. NDVI was found to have a significant impact on water quality within one of four study streams. Stream characteristics related to channel morphology and hydrology should be considered when planning forest conservation if the objective is to improve local water quality.

AUTHOR CONTRIBUTIONS

Tessa Farthing: Data curation; formal analysis; investigation; methodology; supervision; validation; visualization; writing – original draft; writing – review and editing. **Eileen Rintsch:** Investigation; methodology; writing – review and editing. **Owen Larson:** Investigation; methodology; writing – review and editing. **Bartosz P. Grudzinski:** Conceptualization; funding acquisition; investigation; methodology; resources; supervision; validation; writing – original draft; writing – review and editing. **Thomas J. Fisher:** Conceptualization; data curation; formal analysis; methodology; software; supervision; validation; visualization; writing – review and editing. **Jessica L. McCarty:** Formal analysis; methodology; software; supervision; validation; visualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors do not have any conflicts of interest to report.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

REFERENCES

Alexander, R.B., R.A. Smith, and G.E. Schwarz. 2000. "Effect of Stream Channel Size on the Delivery of Nitrogen to the Gulf of Mexico." *Nature* 403(6771): 758–61. https://doi.org/10.1038/35001562.

Andersen, I.M., T.J. Williamson, M.J. González, and M.J. Vanni. 2019. "Nitrate, Ammonium, and Phosphorus Drive Seasonal Nutrient Limitation of Chlorophytes, Cyanobacteria, and Diatoms in a Hyper-Eutrophic Reservoir." *Limnology and Oceanography* 65(5): 962–78. https://doi.org/10.1002/lno.11363.

Armstrong, R.A. 2014. "When to Use the Bonferroni Correction." *Ophthalmic and Physiological Optics* 34(5): 502–08. https://doi.org/10.1111/opo.12131.

Arntzen, E.V., D.R. Geist, and P.E. Dresel. 2006. "Effects of Fluctuating River Flow on Groundwater/Surface Water Mixing in the Hyporheic Zone of a Regulated, Large Cobble Bed River." *River Research and Applications* 22(8): 937–46. https://doi.org/10.1002/RRA.947.

Bernot, M.J., and W.K. Dodds. 2005. "Nitrogen Retention, Removal, and Saturation in Lotic Ecosystems." *Ecosystems* 8(4): 442–53. https://doi.org/10.1007/s10021-003-0143-y.

Bernot, M.J., J.L. Tank, T.V. Royer, and M.B. David. 2006. "Nutrient Uptake in Streams Draining Agricultural Catchments of the Midwestern United States." *Freshwater Biology* 51(3): 499–509. https://doi.org/10.1111/j.1365-2427.2006.01508.x.

Bishop, P.L., W.D. Hively, J.R. Stedinger, M.R. Rafferty, J.L. Lojpersberger, and J.A. Bloomfield. 2005. "Multivariate Analysis of Paired Watershed Data to Evaluate Agricultural Best Management Practice Effects on Stream Water Phosphorus." *Journal of Environmental Quality* 34(3): 1087–101. https://doi.org/10.2134/jeq2004.0194.

Bosompemaa, P., E.W. Peterson, W. Perry, and W.M. Seyoum. 2021. "Recycling of Nitrate and Organic Matter by Plants in the Vadose Zone of a Saturated Riparian Buffer." *Water, Air, and Soil Pollution* 41(1): 232–45. https://doi.org/10.1007/s11270-021-05202-3.

Burnham, K.P., and D.R. Anderson. 2004. "Multimodel Inference: Understanding AIC and BIC in Model Selection." *Sociological Methods & Research* 33(2): 261–304. https://doi.org/10.1177/0049124104268644.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. "Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen." *Ecological Applications* 8(3): 559–68. https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2.

Chaffin, J.D., D.D. Kane, K. Stanislawczyk, and E.M. Parker. 2018. "Accuracy of Data Buoys for Measurement of Cyanobacteria, Chlorophyll, and Turbidity in a Large Lake (Lake Erie, North America): Implications for Estimation of Cyanobacterial Bloom Parameters from Water Quality Sonde Measurements." *Environmental Science and Pollution Research* 25(25): 25175–89. https://doi.org/10.1007/s11356-018-2612-z.

Chen, D., J. Lu, H. Wang, Y. Shen, and M.O. Kimberley. 2010. "Seasonal Variations of Nitrogen and Phosphorus Retention in an Agricultural Drainage River in East China." *Environmental Science and Pollution Research* 17: 312–20. https://doi.org/10.1007/s11356-009-0246-x.

Covino, T. 2017. "Hydrologic Connectivity as a Framework for Understanding Biogeochemical Flux through Watersheds and along Fluvial Networks." *Geomorphology* 277: 133–44. https://doi.org/10.1016/j.geomorph.2016.09.030.

Cressie, N.A., and H.J. Whitford. 1986. "How to Use the Two Sample t-Test." *Biometrical Journal* 28(2): 131–48. https://doi.org/10.1002/bimj.4710280202.

Debrewer, L.M., G.L. Rowe, D.C. Reutter, R.C. Moore, J.A. Hambrook, and N.T. Baker. 2000. "Environmental Setting and Effects on Water Quality in the Great and Little Miami River Basins, Ohio and Indiana." U.S. Geological Survey Water-Resources Investigations Report 1999–420. https://doi.org/10.3133/wri994201.

Dodds, W., and V. Smith. 2016. "Nitrogen, Phosphorus, and Eutrophication in Streams." *Inland Waters* 6(2): 155–64. https://doi.org/10.5268/IW-6.2.909.

Dodds, W.K., V.H. Smith, and K. Lohman. 2002. "Nitrogen and Phosphorus Relationships to Benthic Algal Biomass in Temperate Streams." *Canadian Journal of Fisheries and Aquatic Sciences* 59(5): 865–74. https://doi.org/10.1139/f02-063.

Doyle, M.W. 2005. "Incorporating Hydrologic Variability into Nutrient Spiraling." *Journal of Geophysical Research* 110(G1): 1–11. https://doi.org/10.1029/2005JG000015.

Ensign, S.H., and M.W. Doyle. 2006. "Nutrient Spiraling in Streams and River Networks." *Journal of Geophysical Research: Biogeosciences* 111(G4): 1–13. https://doi.org/10.1029/2005JG000114.

Falcone, J.A., J.C. Murphy, and L.A. Sprague. 2018. "Regional Patterns of Anthropogenic Influences on Streams and Rivers in the Conterminous United States, from the Early 1970s to 2012." *Journal of Land Use Science* 13(6): 585–614. https://doi.org/10.1080/1747423X.2019.1590473.

Finkler, N.R., F. Tromboni, I. Boëchat, B. Gücker, and D.G.F. Cunha. 2018. "Nitrogen and Phosphorus Uptake Dynamics in Tropical Cerrado Woodland Streams." *Water* 10(8): 1080. https://doi.org/10.3390/w10081080.

Fisher, T.J., and C.M. Gallagher. 2012. "New Weighted Portmanteau Statistics for Time Series Goodness of Fit Testing." *Journal of the American Statistical Association* 107(498): 777–87. https://doi.org/10.1080/01621459.2012.688465.

Giri, S., and Z. Qiu. 2016. "Understanding the Relationship of Land Uses and Water Quality in Twenty First Century: A Review." *Journal of Environmental Management* 173: 41–48. https://doi.org/10.1016/j.jenvman.2016.02.029.

Gorelick, N., M. Hancher, M. Dixon, S. Ilyushchenko, D. Thau, and R. Moore. 2017. "Google Earth Engine: Planetary-Scale Geospatial Analysis for Everyone." *Remote Sensing of Environment* 202: 18–27. https://doi.org/10.1016/j.rse.2017.06.031.

Grabow, G.L., J. Spooner, L.A. Lombardo, and D.E. Line. 1999. "Detecting Water Quality Changes before and after BMP Implementation: Use of SAS for Statistical Analysis." NWQEP Notes 93. https://319monitoring.wordpress.ncsu.edu/files/2016/05/93.pdf.

Griffith, J.A., E.A. Martinko, J.L. Whistler, and K.P. Price. 2002. "Interrelationships among Landscapes, NDVI, and Stream Water Quality in the U.S. Central Plains." *Ecological Applications* 12(6): 1702–18. https://doi.org/10.1890/1051-0761(2002)012[1702:IALNAS]2.0.CO;2.

Grudzinski, B.P., and M.D. Daniels. 2018. "Bison and Cattle Grazing Impacts on Grassland Stream Morphology in the Flint Hills of Kansas." *Rangeland Ecology & Management* 71(6): 783–91. https://doi.org/10.1016/j.rama.2018.06.007.

Grudzinski, B.P., K. Fritz, and W. Dodds. 2020. "Does Riparian Fencing Protect Stream Water Quality in Cattle-Grazed Lands?" *Environmental Management* 66: 121–35. https://doi.org/10.1007/s00267-020-01297-2.

Hamilton, S.K., J.L. Tank, D.F. Raiken, W.M. Wollheim, B.J. Peterson, and J.R. Webster. 2001. "Nitrogen Uptake and Transformation in a Midwestern U.S. Stream: A Stable Isotope Enrichment Study." *Biogeochemistry* 54(3): 297–340. https://doi.org/10.1023/A:1010635524108.

Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy. 1994. "Stream Channel Reference Sites: An Illustrated Guide to Field Technique." USDA Forest Service General Technical Report RM-245. https://doi.org/10.2737/RM-GTR-245.

Herschy, R.W. 1998. "Velocity-Area Method." *Encyclopedia of Earth Science*, 668–70. https://doi.org/10.1007/978-1-4020-4497-7_228.

Hill, A.R. 2017. "Landscape Hydrogeology and its Influence on Patterns of Groundwater Flux and Nitrate Removal Efficiency in Riparian Buffers." *Journal of the American Water Resources Association* 54(1): 240–54. https://doi.org/10.1111/1752-1688.12606.

Hill, A.R., C.F. Labadia, and K. Sanmugadas. 1998. "Hyporheic Zone Hydrology and Nitrogen Dynamics in Relation to the Streambed Topography of a N-Rich Stream." *Biogeochemistry* 42(3): 285–310. https://doi.org/10.1023/A:1005932528748.

Jansson, M., R. Andersson, H. Berggren, and L. Leonardson. 1994. "Denitrification and Nitrogen Retention in a Farmland Stream in Southern Sweden." *Ambio* 23: 326–31. https://doi.org/10.1023/A:1017506914063.

Johnson, J.B., and K.S. Omland. 2004. "Model Selection in Ecology and Evolution." *Trends in Ecology & Evolution* 19(2): 101–08. https://doi.org/10.1016/j.tree.2003.10.013.

Kalkhoff, S., L. Hubbard, M. Tomer, and D. James. 2016. "Effect of Variable Annual Precipitation and Nutrient Input on Nitrogen and Phosphorus Transport from Two Midwestern Agricultural Watersheds." *Science of the Total Environment* 559: 53–62. https://doi.org/10.1016/j.scitotenv.2016.03.127.

Kelly, P.T., W.H. Renwick, L. Knoll, and M.J. Vanni. 2019. "Stream Nitrogen and Phosphorus Loads Are Differentially Affected by Storm Events and the Difference May Be Exacerbated by Conservation Tillage." *Environmental Science & Technology* 53(10): 5613–21. https://doi.org/10.1021/acs.est.8b05152.

Kreiling, R.M., M.C. Thoms, L.A. Bartsch, W.B. Richardson, and V.G. Christensen. 2019. "Complex Response of Sediment Phosphorus to Land Use and Management within a River Network." *Journal of Geophysical Research: Biogeosciences* 124(7): 1764–80. https://doi.org/10.1029/2019JG005171.

Kusmer, A.S., J.O. Goyette, G.K. Macdonald, E.M. Bennett, R. Maranger, and P.J.A. Withers. 2018. "Watershed Buffering of Legacy Phosphorus Pressure at a Regional Scale: A Comparison across Space and Time." *Ecosystems* 22(1): 91–109. https://doi.org/10.1007/s10021-018-0255-z.

Lazar, J.A., R. Spahr, B.P. Grudzinski, and T.J. Fisher. 2019. "Land Cover Impacts on Storm Flow Suspended Solid and Nutrient Concentrations in Southwest Ohio Streams." *Water Environment Research* 91(6): 510–22. https://doi.org/10.1002/wer.1054.

Lee, P., C. Smyth, and S. Boutin. 2004. "Quantitative Review of Riparian Buffer Width Guidelines from Canada and the United States." *Journal of Environmental Management* 70(2): 165–80. https://doi.org/10.1016/j.jenvman.2003.11.009.

Lefebvre, S., P. Marmonier, G. Pinay, O. Bour, L. Aquilina, and J. Baudry. 2005. "Nutrient Dynamics in Interstitial Habitats of Low-Order Rural Streams with Different Bedrock Geology." *Archiv für Hydrobiologie* 164(2): 169–91. https://doi.org/10.1127/0003-9136/2005/0164-0169.

Lowrance, R., L.S. Altier, J.D. Newbold, R.R. Schnabel, P.M. Groffman, J.M. Denver, D.L. Correll, J.W. Gilliam, and J.L. Robinson. 1997. "Water Quality Functions of Riparian Forest Buffers in Chesapeake Bay Watersheds." *Environmental Management* 21(5): 687–712. https://doi.org/10.1007/s002679900060.

Lowrance, R., R. Todd, J. Fail, O. Hendrickson, R. Leonard, and L. Asmussen. 1984. "Riparian Forests as Nutrient Filters in Agricultural Watersheds." *Bioscience* 34(6): 374–77. https://doi.org/10.2307/1309729.

Meals, D.W., S.N. Levine, D. Wang, J.P. Hoffmann, E.A. Cassell, J.C. Drake, D.K. Pelton, H.M. Galarneau, and A.B. Brown. 1999. "Retention of Spike Additions of Soluble Phosphorus in a Northern Eutrophic Stream." *Journal of the North American Benthological Society* 18(2): 185–98. https://doi.org/10.2307/1468460.

Mello, K.D., R.A. Valente, T.O. Randhir, A.C.A.D. Santos, and C.A. Vettorazzi. 2018. "Effects of Land Use and Land Cover on Water Quality of Low-Order Streams in Southeastern Brazil: Watershed versus Riparian Zone." *Catena* 167: 130–38. https://doi.org/10.1016/j.catena.2018.04.027.

Nielsen, A., D. Trolle, M. Søndergaard, T.L. Lauridsen, R. Bjerring, J.E. Olesen, and E. Jeppesen. 2012. "Watershed Land Use Effects on Lake Water Quality in Denmark." *Ecological Applications* 22(4): 1187–200. https://doi.org/10.1890/11-1831.1.

Oki, K., and Y. Yasuoka. 2008. "Mapping the Potential Annual Total Nitrogen Load in the River Basins of Japan with Remotely Sensed Imagery." *Remote Sensing of Environment* 112: 3091–98. https://doi.org/10.1016/j.rse.2008.03.006.

Olson, K.R., R.L. Jones, and J.M. Lang. 2005. "Soil Formation at Millstone Bluff and Johnson Ridge in Southern Illinois." *Soil Science* 170(6): 457–68. https://doi.org/10.1097/01.ss.0000169917.63474.d6.

Opdyke, M.R., M.B. David, and B.L. Rhoads. 2006. "Influence of Geomorphological Variability in Channel Characteristics on Sediment Denitrification in Agricultural Streams." *Journal of Environmental Quality* 35(6): 2103–12. https://doi.org/10.2134/jeq2006.0072.

Ostrofsky, M.L., A.G. Stolarski, and K.A. Dagen. 2018. "Export of Total, Particulate, and Apatite Phosphorus from Forested and Agricultural Watersheds." *Journal of Environmental Quality* 47(1): 106–12. https://doi.org/10.2134/jeq2017.06.0227.

Ouyang, W., X. Wang, F. Hao, and R. Srinivasan. 2009. "Temporal–Spatial Dynamics of Vegetation Variation on Non-Point Source Nutrient Pollution." *Ecological Modelling* 220(20): 2702–13. https://doi.org/10.1016/j.ecolmodel.2009.06.039.

Peterjohn, W.T., and D.L. Correll. 1984. "Nutrient Dynamics in an Agricultural Watershed: Observations on the Role of a Riparian Forest." *Ecology* 65(5): 1466–75. https://doi.org/10.2307/1939127.

Petry, J., C. Soulsby, I. Malcolm, and A. Youngson. 2002. "Hydrological Controls on Nutrient Concentrations and Fluxes in Agricultural Catchments." *Science of the Total Environment* 294(1–3): 95–110. https://doi.org/10.1016/S0048-9697(02)00058-X.

QGIS Development Team. 2009. "QGIS Geographic Information System." Open Source Geospatial Foundation. http://qgis.org.

Rech, J.A., B. Grudzinski, W.H. Renwick, C.N. Tenison, M. Jojola, M.J. Vanni, and T.R. Workman. 2018. "Legacy Deposits, Milldams, Water Quality, and Environmental Change in the Four Mile Creek Watershed, Southwestern Ohio." Ancient Oceans, Orogenic Uplifts, and Glacial Ice: Geologic Crossroads in America's Heartland. https://doi.org/10.1130/2018.0051(05).

Reed, B.C., J.F. Brown, D. VanderZee, T.R. Loveland, J.W. Merchant, and D.O. Ohlen. 1994. "Measuring Phenological Variability from Satellite Imagery." *Journal of Vegetation Science* 5(5): 703–14. https://doi.org/10.2307/3235884.

Renwick, W.H., M.J. Vanni, T.J. Fisher, and E.L. Morris. 2018. "Stream Nitrogen, Phosphorus, and Sediment Concentrations Show Contrasting Long-Term Trends Associated with Agricultural Change." *Journal of Environmental Quality* 47(6): 1513–21. https://doi.org/10.2134/jeq2018.04.0162.

Robinson, N., B. Allred, M. Jones, A. Moreno, J. Kimball, D. Naugle, T. Erickson, and A. Richardson. 2017. "A Dynamic Landsat Derived Normalized Difference Vegetation Index (NDVI) Product for the Conterminous United States." *Remote Sensing* 9(8): 863. https://doi.org/10.3390/rs9080863.

Roley, S.S., J.L. Tank, and M.A. Williams. 2012. "Hydrologic Connectivity Increases Denitrification in the Hyporheic Zone and Restored Floodplains of an Agricultural Stream." *Journal of Geophysical Research: Biogeosciences* 117(G3): 1–16. https://doi.org/10.1029/2012JG001950.

Royer, T.V., J.L. Tank, and M.B. David. 2004. "Transport and Fate of Nitrate in Headwater Agricultural Streams in Illinois." *Journal of Environmental Quality* 33(4): 1296–304. https://doi.org/10.2134/jeq2004.1296.

Schade, J.D., K. Macneill, S.A. Thomas, F.C. Mcneely, J.R. Welter, J. Hood, M. Goodrich, M.E. Power, and J.C. Finlay. 2010. "The Stoichiometry of Nitrogen and Phosphorus Spiraling in Heterotrophic and Autotrophic Streams." *Freshwater Biology* 56(3): 424–36. https://doi.org/10.1111/j.1365-2427.2010.02509.x.

Shrestha, S., and F. Kazama. 2007. "Assessment of Surface Water Quality Using Multivariate Statistical Techniques: A Case Study of the Fuji River Basin, Japan." *Environmental Modelling & Software* 22(4): 464–75. https://doi.org/10.1016/j.envsoft.2006.02.001.

United States Environmental Protection Agency. 2016. "Monitoring and Evaluating Nonpoint Source Watershed Projects.". https://www.epa.gov/sites/default/files/2016-06/documents/nps_monitoring_guide_may_2016-combined_plain.pdf.

Uwimana, A., A. Van Dam, G. Gettel, B. Bigirimana, and K. Irvine. 2017. "Effects of River Discharge and Land Use and Land Cover (LULC) on Water Quality Dynamics in Migina Catchment, Rwanda." *Environmental Management* 60(3): 496–512. https://doi.org/10.1007/s00267-017-0891-7.

Van Meter, K.J., P. Van Cappellen, and N.B. Basu. 2018. "Legacy Nitrogen May Prevent Achievement of Water Quality Goals in the Gulf of Mexico." *Science* 360: 427–30. https://doi.org/10.1126/science.aar4462.

Vanni, M.J., W.H. Renwick, J.L. Headworth, J.D. Auch, and M.H. Schaus. 2001. "Dissolved and Particulate Nutrient Flux from Three Adjacent Agricultural Watersheds: A Five-Year Study." *Biogeochemistry* 54(1): 85–114. https://doi.org/10.1023/A:1010681229460.

Vega, M., R. Pardo, E. Barrado, and L. Debán. 1998. "Assessment of Seasonal and Polluting Effects on the Quality of River Water by Exploratory Data Analysis." *Water Research* 32(12): 3581–92. https://doi.org/10.1016/S0043-1354(98)00138-9.

Vidon, P., and A.P. Smith. 2007. "Upland Controls on the Hydrological Functioning of Riparian Zones in Glacial till Valleys of the Midwest." *Journal of the American Water Resources Association* 43(6): 1524–39. https://doi.org/10.1111/j.1752-1688.2007.00125.x.

Wallbrink, P., C. Martin, and C. Wilson. 2003. "Quantifying the Contributions of Sediment, Sediment-P and Fertiliser-P from Forested, Cultivated and Pasture Areas at the Landuse and Catchment Scale Using Fallout Radionuclides and Geochemistry." *Soil and Tillage Research* 69(1–2): 53–68. https://doi.org/10.1016/S0167-1987(02)00128-9.

Webber, J.A., K.J. Willard, M.R. Whiles, M.L. Stone, J.J. Zaczek, and D.K. Davie. 2003. "Watershed Scale Assessment of the Impact of Forested Riparian Zones on Stream Water Quality." United States Department of Agriculture Proceedings of the 13th Central Hardwood Forest Conference; Gen. Tech. Rep. 114–20. https://www.fs.usda.gov/treesearch/pubs/15731.

Weigelhofer, G., T. Hein, and E. Bondar-Kunze. 2018. “Phosphorus and Nitrogen Dynamics in Riverine Systems: Human Impacts and Management Options.” Riverine Ecosystem Management, 187–202. https://doi.org/10.1007/978-3-319-73250-3.

Withers, P., and H. Jarvie. 2008. “Delivery and Cycling of Phosphorus in Rivers: A Review.” *Science of the Total Environment* 400(1–3): 379–95. https://doi.org/10.1016/j.scitotenv.2008.08.002.

Wolman, M.G. 1954. “A Method of Sampling Coarse River-Bed Material.” *Transactions, American Geophysical Union* 35(6): 951–56. https://doi.org/10.1029/TR035i006p00951.

Zhu, J., X. Wang, L. Zhang, H. Cheng, and Z. Yang. 2015. “System Dynamics Modeling of the Influence of the TN/TP Concentrations in Socioeconomic Water on NDVI in Shallow Lakes.” *Ecological Engineering* 76: 27–35. https://doi.org/10.1016/j.ecoleng.2014.06.030.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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