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Influence of Climate and Human Activities on the Relationship between Watershed Nitrogen Input and River Export

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River export of nitrogen (N) is influenced strongly by spatial variation in anthropogenic N inputs and climatic variation. We developed a model of riverine N export for 18 Lake Michigan Basin watersheds based on N budgets at 5-year intervals from 1974 to 1992. N inputs explained a high proportion of the spatial variation in river export but virtually none of the temporal variation, whereas between year N export was related to variation in discharge for over one-half of the rivers. A regression model of riverine N exports as an exponential function of N inputs and a power function of annual water discharge accounted for 87% of the variation in annual total nitrogen fluxes over space and time. Application of this model to three scenarios of future land use, including business as usual, greater reliance on organic farming methods, and expanded corn-based ethanol production, and two climate scenarios, including increases in water discharge by 5% and 10%, suggests that riverine N export is likely to increase by as much as 24% in response to heavier fertilizer use for expanded corn production and a 10% increase in annual discharge. However, N export by rivers could decrease below present-day export through reduced reliance on commercial fertilizer use.

Introduction

Human activities, including fossil fuel combustion, fertilizer application, and cultivation of N-fixing crops, have significantly increased reactive nitrogen (N) load to watersheds and its subsequent riverine flux to lakes and coastal areas (*1*). In addition, river N export is greater in wet years (*2, 3*) and wet regimes (*4*). Thus, changes in human activities, such as expanded ethanol production, and potentially higher river discharge under future climates may further influence N watershed loading and river export. To better understand factors influencing N delivery to aquatic systems and thus potential harmful effects such as eutrophication and hypoxia (*5*), models that predict N export should be responsive to anthropogenic activities and hydrologic variation.

Mass balance approaches have been used widely to explore the relationship between N loading to watersheds and river export (*6, 7*). Most studies using a NANI (Net Anthropogenic Nitrogen Input) approach have shown that either spatial (*6, 7*) or temporal (*2*) variation in river N export can largely be explained as a function of NANI, the sum of N inputs from fertilizer, atmospheric deposition, and plant N fixation, and the net of nitrogen imported and exported in food and feed (*7*). Several studies suggest that 20−25% of NANI is exported by rivers with the remainder either retained or denitrified (*6*−*8*), although that fraction varies with land use (*9, 10*) and is less in low-latitude watersheds (*11*).

Although the relationship between NANI and river N export is strong (*6, 7*), some remaining variance is associated with between-watershed and between-year variation in precipitation, discharge, and temperature. For 16 watersheds of the northeastern United States, those with higher precipitation and discharge exported a higher fraction of NANI, whereas drier watersheds exported a lower fraction relative to the overall input−export relationship (*4*). Comparison of these sites to 12 watersheds of the southeastern United States showed the fractional delivery to vary exponentially with temperature above a breakpoint between 11 and 12 °C (*11*). However, these findings are all based on spatial comparisons across different climates, and so their applicability to interannual variation in climate is uncertain. A strong temporal relationship was documented between N inputs and annual riverine nitrate exports for the lower Mississippi River Basin, demonstrating the importance of interannual variation in precipitation and hydrology (*2*). In Baltimore-area urban streams nitrate concentrations in streamwater and fractional export of N inputs exhibited interannual variation with lower values in dry years and higher values in wet years (*9, 10*).

Few studies have simultaneously considered both spatial and temporal variation in N inputs over a range of N sources, watersheds, and climatic conditions when establishing the relationship between watershed inputs and river exports. By employing both time series and spatial data simultaneously it is possible to develop a reliable model without any loss of information that would result from averaging temporal or spatial data. A model that incorporates temporal change across multiple watersheds should improve our ability to forecast river export in response to future climate and land use scenarios.

Here, we estimate anthropogenic N inputs, riverine N exports, and data for other landscape and climatic characteristics for 18 watersheds of the Lake Michigan Basin for five time periods between 1974 and 1992. We employed a cross-sectional time series analysis using regression for panel data, a technique used where relationships among multiple spatial variables are observed over two or more time periods (*12, 13*). Our primary objective was to develop a predictive model of river N export that has utility for forecasting N loading in response to possible changes in anthropogenic activities and climate.

Methods

We examined spatial and temporal trends for a variety of anthropogenic N inputs and outputs for 18 watersheds (Figure 1) selected from the approximately 25 watersheds that comprise the Lake Michigan Basin based on available river export data (*14*). They cover an area of approximately 85 050 km^2, 73% of the total area of the Lake Michigan Basin, and range in size from 153 (Trail Creek) to 15 825 km^2 (Fox River). The combined landscapes of the 18 watersheds were 43% agricultural, 37% forest, 12% wetland, and 6% urban in the year 1992 (*15*). However, land use varies widely among watersheds with a general northerly trend from agricultural to forested land. The five time intervals (1974, 1978, 1982,

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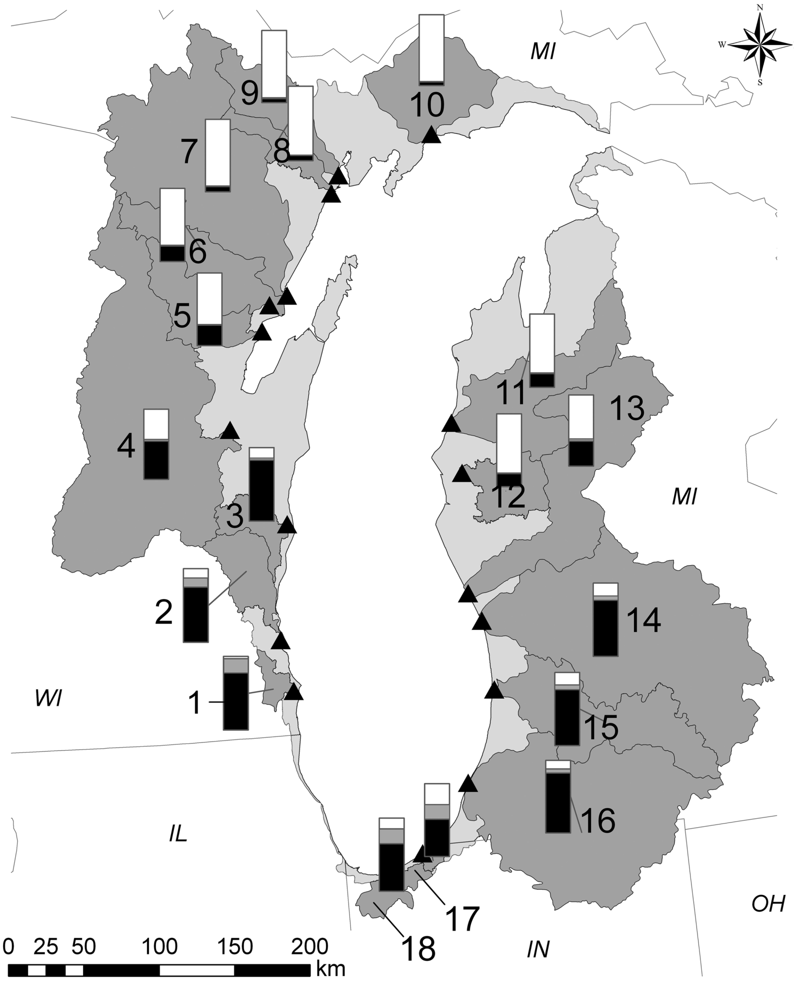

FIGURE 1. Eighteen watersheds of the Lake Michigan Basin selected for N input−export estimation. The watersheds include the following: Root (1), Milwaukee (2), Sheboygan (3), Fox (4), Oconto (5), Peshtigo (6), Menominee (7), Ford (8), Escanaba (9), Manistique (10), Manistee (11), Pere Marquette (12), Muskegon (13), Grand (14), Kalamazoo (15), St. Joseph (16), Trail Creek (17), and Burns Ditch (18). Triangles are USGS gauging stations. Watersheds not included in this analysis are shown in light gray. Bar charts show the percentages of land that is undisturbed (forest and wetland) in white, agriculture in black, and urban in gray.

1987, 1992) represent agricultural census years during which river export TN estimates were available. Annual precipitation for each census year was obtained from PRISM historical climate GIS data set (4 km × 4 km) (*16*), and grid values within each catchment were averaged using ArcGIS 9.0.

NANI was estimated based on the difference between anthropogenic N inputs including atmospheric N deposition, crop N fixation, fertilizer, and food and feed imports and outputs due to N volatilization and export of food and feed (*17*). NANI only considers N that is either newly fixed within a system or transported into a system from outside sources (*7, 14*)(Supporting Information).

Annual TN exported from each tributary was calculated from TN concentrations and daily discharge data using the USGS Estimator Regression Model (*18*). Data for TN concentrations for 1960−1995 were retrieved from the USGS National Water Information System and the U.S. Environmental Protection Agency Storage and Retrieval System. Daily streamflow data were obtained from the USGS National Water Data Storage and Retrieval System. Approximately monthly TN concentrations were available for most watershed export estimates. Where data were limited we used TN concentrations from multiple nearby monitoring stations within the same catchment. We estimated TN export for each calendar year after first calibrating the USGS estimator regression model with 5 years of continuous data (on average ∼67−107 points for 18 watersheds) (*17*). See Tables S1 and S2 (Supporting Information) for monitoring site locations, landscape characteristics, and climate data.

A panel data regression model was used to describe spatial and temporal variation in TN export for the 18 Lake Michigan watersheds and the 5 years based on NANI estimates and climatic variables. Panel data regression minimizes bias resulting from omitted variables by allowing individual years to have different intercepts (a fixed effect model) or alternatively to select an overall intercept with different composite error terms that measure the extent to which individual intercepts for each year differ from the overall intercept (a random effect model) (*13*) (Supporting Information). By exploiting information on temporal relationships between watershed N input and riverine export for each watershed, panel data regression also avoids the need for a lengthy time series to understand the dynamic behavior of the regression relationship (*12*).

To select the appropriate model we hierarchically tested three null hypotheses (Figure S1, Supporting Information). We first tested the null hypothesis that intercepts and slopes are equal across years using the Chow test (*19*) in the AUTOREG procedure of the SAS (SAS Institute Inc.) statistical package. If this null is accepted data are pooled and analyzed in ordinary least-squares (OLS) regression. If this hypothesis is rejected the second null hypothesis that slopes of individual regressions are constant over time is tested by running OLS

TABLE 1. Riverine Total Nitrogen Exports and NANI for the 18 Lake Michigan Watersheds and 5 Agricultural Census Years

		riverine TN exports(kg-N km^{-2} yr^{-1})					NANI (kg-N km^{-2} yr^{-1})				
ID	watershed	1974	1978	1982	1987	1992	1974	1978	1982	1987	1992
1	Root	1663	1762	2239	1213	1063	5715	5635	5658	6147	5753
2	Milwaukee	815	697	863	441	468	3,881	3758	4052	4762	3913
3	Sheboygan	888	1009	1120	462	578	3577	4405	5250	6248	5418
4	Fox	334	384	462	316	410	2290	2349	2821	3628	2691
5	Oconto	483	553	286	135	387	1273	1648	1794	2170	1603
6	Peshtigo	206	233	245	147	287	932	1112	1304	1365	1239
7	Menominee	174	210	292	161	191	716	743	955	862	913
8	Ford	193	267	267	156	174	851	940	1253	1086	1153
9	Escanaba	176	301	256	163	186	688	732	879	665	820
10	Manistique	286	373	325	209	256	685	732	905	720	774
11	Manistee	252	227	217	221	224	999	1106	1400	1390	1366
12	Pere Marquette	336	386	304	309	154	1195	1382	1699	1849	1863
13	Muskegon	309	264	280	282	330	1262	1428	1863	2015	1985
14	Grand	871	620	760	572	1061	2794	3251	3763	4716	4308
15	Kalamazoo	591	582	593	495	633	2659	2960	3428	4345	3632
16	St. Joseph	788	874	1133	650	806	3679	3442	4622	4922	4960
17	Trail Creek	687	888	979	683	921	3607	4064	4935	4106	4766
18	Burns Ditch	1415	859	1538	1275	1039	5304	5635	6354	6262	5750

regressions for each time period and from the F-statistic calculated as

$$F_{obs} = \frac{(\mathrm{SSE}' - \sum_{1}^{T} SSE_t)/(T-1)K}{\sum_{1}^{T} SSE_t/(n-K)} \sim F[(T-1)K, T(n-K)] \quad (1)$$

where n is the number of watersheds, T is the number of years, K is the number of regressors plus 1 (including the intercept), SSE′ is the sum of squared errors (SSE) of the pooled OLS, and $\mathrm{SSE_t}$ is the SSE of the OLS regression for year t ($t = 1-T$). Accepting this hypothesis indicates that only intercepts vary by year and either a fixed effects or random effects model should be used. The random effects model is a more efficient estimator of slope than the fixed effects model unless the error term is correlated with the explanatory variables because the random effects model can produce estimates of coefficients using information from the 18 Lake Michigan watersheds within a single year as well as between years. Therefore, the random effects model should be used if it is statistically justifiable to do so. As a final step, the third null hypothesis that random effects estimates are unbiased is assessed using the Hausman test (*20*). In addition to examining the R^2 value and root-mean-square error (RMSE) we evaluated the accuracy of the panel data model using an error analysis (*21*) (Supporting Information).

To forecast future trends in NANI to 2020 we estimated additional NANI budgets for the 1997 and 2002 census years (*7, 14*) (Supporting Information), calculated an average NANI for the period from 1992 to 2002 as a baseline, and developed forecasts of future trends of NANI based on three assumptions. First, we assumed that temporal trends in NANI will continue to be determined by current agricultural production strategies, including the major cash crops, contributions of livestock versus crop sectors to the agroeconomy of the Lake Michigan Basin, and existing farming practices. Second, the extent of farmland and cropland is assumed to remain constant at the baseline level (~25% and ~40% of the 18 Lake Michigan watersheds presently is in cropland and farmland). Third, human population in 2020 is assumed to increase by 5% (MI), 10% (IL), 11% (IN), and 11% (WI) from 2000, based on the U.S. Bureau of the Census projections (*22*).

We then developed three scenarios for analysis: "status quo", "organic future", and "biofuel future". Our status-quo scenario assumed that future NANI will change only due to population increases and other components of the NANI budget will remain constant except for those driven by human population size. Our "organic future" assumed that agriculture in the eastern and southern regions of the Lake Michigan basin mimics the baseline practices in the western Lake Michigan basin, relying on hay-corn rotation, extensive pasture land for grazing, manure-based cropping system, and avoiding the use of inorganic fertilizer (see the Supporting Information for more details). Our "biofuel future" assumes that the Lake Michigan basin will rely on intensive corn production of conventional fertilizer-based agro-ecosystems to expand corn-based ethanol production according to a USDA agricultural projection to 2017 (*23*) (Supporting Information). Finally, to forecast how different NANI scenarios and future climate conditions might affect future riverine TN exports we used eq 4 that we developed to predict river export from NANI and discharge, the three estimates of future NANI, and two hypothetical scenarios in which future water discharge increased by 5% and 10% (*24−26*) (Supporting Information).

Results

NANI Budgets. No temporal trends in NANI were observed between 1974 and 1992, but time-averaged NANI varied across watersheds, ranging from 757 to 5861 kg-N km^{-2} yr^{-1} (Table 1). Spatial variability (standard deviation (s) = 1636 kg-N km^{-2} yr^{-1} in 1974 to 2041 kg-N km^{-2} yr^{-1} in 1987) for each year was much larger than temporal variability over the five agricultural census years for each watershed ($s = 85$ kg-N km^{-2} yr^{-1} in Manistique to 1021 kg-N km^{-2} yr^{-1} in Sheboygan). This spatial pattern of NANI was consistent with reported values ranging from forested catchments of Maine (*4*) to agricultural catchments in the Mississippi River Basin (*27*) and the North Sea Basin of Europe (*7*). For each of five census years NANI was positively correlated with annual population density ($R^2 = 0.5$ (1987) to 0.6 (1974), $p < 0.05$)). The estimate in 1992 was also positively related with the percentage of a watershed in agricultural ($R^2 = 0.73$) and in disturbed land (agriculture + urban; $R^2 = 0.84$), consistent with other studies (*6*).

The magnitude and relative importance of individual N inputs varied widely among watersheds (Figure S2, Supporting Information). Fertilizer (~34−42% of total NANI) and crop N fixation (~34−40%) were major inputs for the agricultural west-central region, net atmospheric N deposition (~46−80% of total NANI) was the largest source in the

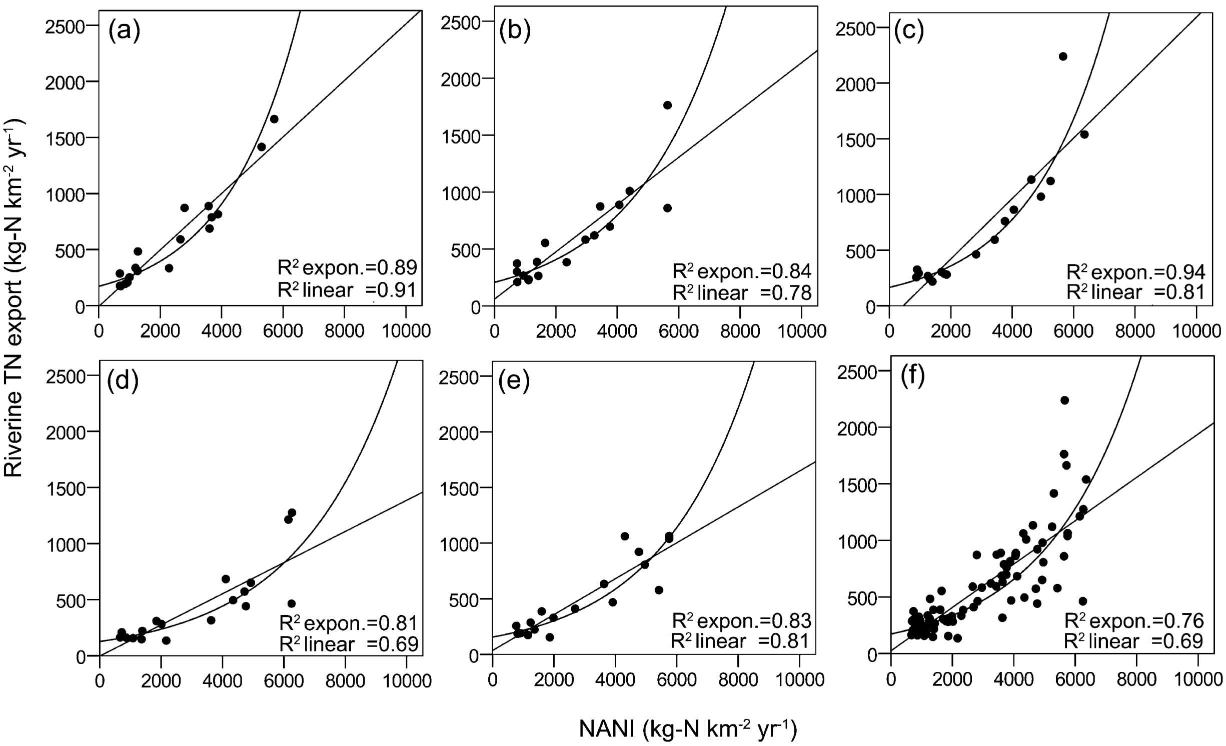

FIGURE 2. Scatter plots showing the spatial relationship between NANI and annual TN exports from 18 Lake Michigan watersheds and the change in the input−export relationship over five different years (a) 1974, (b) 1978, (c) 1982, (d) 1987, (e) 1992. (f) Input−export relationship using pooled data from 18 Lake Michigan watersheds for all five years.

northern region, and N fertilizer (∼42−49% of total NANI) was the largest source for the southeastern region of the Lake Michigan Basin.

Riverine N Exports in Relation to NANI. Annual TN export across the 18 watersheds and 5 years (Table 1) ranged from 135 to 2239 kg-N km^{-2} yr^{-1}. TN yields for these rivers fall within the range of recent estimates for forested watersheds of northeastern United States (*6*), major agricultural watersheds in Illinois (*28*), and mixed urban and agricultural watersheds (*6*). For the 90 (=18 × 5) estimates of TN export the median was 387 kg-N km^{-2} yr^{-1} and the range from the first to third quartiles was 256 to 802 kg-N km^{-2} yr^{-1}. Spatial variation across the 18 watersheds varied from ∼7-fold in 1992 to ∼17-fold in 1982. Temporal range was considerably smaller, from 1.2-fold in the Manistee to 4.1-fold in the Oconto, and did not exhibit a trend across years.

Using simple linear regression, NANI was the best single variable to account for spatial variation in riverine TN exports for each estimation year, explaining 69% (1987) to 91% (1974) of variation, compared with any individual N input term or any climatic or landscape characteristics of the watersheds (Table S3, Supporting Information). NANI alone accounted for no temporal variation in export across the 5 census years for all watersheds except the Manistee. However, annual water discharge alone accounted for significant temporal variation in TN exports for five watersheds and approached significance ($0.05 < p < 0.10$) for six additional watersheds. Similarly, annual mean precipitation explained 85−95% of temporal variation in TN exports for four watersheds of the Upper Peninsula with less than 10% disturbed area (Table S4, Supporting Information).

Average fractional N delivery from rivers for individual years estimated by slope coefficients of linear regressions between NANI and river N exports are significantly and positively correlated with total water discharge from the 18 Lake Michigan watersheds (Pearson correlation coeff. = 0.856, $p = 0.032$, Figure S3a, Supporting Information) as well as with mean annual precipitation across the 18 watersheds (correlation coeff. = 0.885, $p = 0.032$, Figure S3b, Supporting Information).

An exponential regression model between NANI and river export resulted in higher R^2 values (Figure 2) and smaller RMSE than did a linear model for all years except 1974. While the difference between the two models was not statistically significant, results for pooled data (Figure 2f) suggest that the relationship between NANI and river export is better captured by the exponential model (Supporting Information). It had lower bias (interquartile range = 37.4% averaged over the five years) and stronger prediction symmetry (median error = 0.64%) in comparison to the linear model (interquartile range = 41.6% and median error = −1.4%).

Development of the Panel Data Model and Model Accuracy. The analyses reported above suggest that the relationship between NANI and riverine TN exports is best described using an exponential function (see Supporting Information). In addition, slopes vary among years in relation to interannual variation in discharge (Supporting Information), which is best described by a log−log relationship (not shown) between TN export and discharge. Thus, we developed the following model for riverine TN exports

$$\mathrm{RNEXPORT}_{it} = \alpha \times Q_{it}^{\beta 1} \times \exp(\beta_2 \times \mathrm{NANI}_{it}) \qquad (2)$$

where $\mathrm{RNEXPORT}_{it}$ is riverine TN export (kg-N km^{-2} yr^{-1}) from watershed i in year t, NANI_{it} (kg-N km^{-2} yr^{-1}) is NANI to watershed i in year t, Q_{it} is the annual water discharge (mm/yr) from watershed i in year t, and α, β_1, and β_2 are parameters estimated from the panel data regression. Expressing this in linear form

$$\ln(\mathrm{RNEXPORT}_{it}) = \ln(\alpha) + \beta_1 \times \ln(Q_{it}) + \beta_2 \times \mathrm{NANI}_{it} \qquad (3)$$

Using eq 3 with panel data the Chow test rejected the first null hypothesis that all coefficients (α, β_1, and β_2) are constant over time ($p < 0.05$ for all years), indicating that a pooled OLS regression was not suitable. The test of whether all slopes were equal to the corresponding pooled slope resulted in an

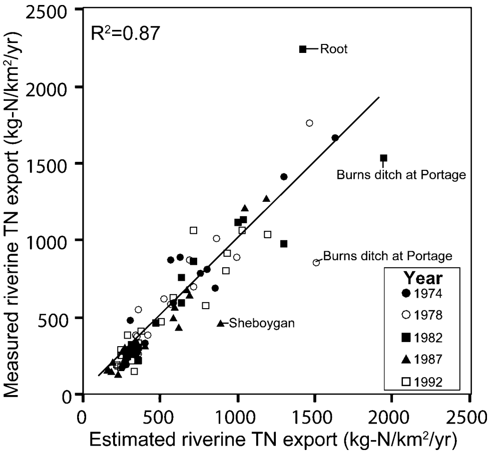

FIGURE 3. Observed river TN export from the 18 Lake Michigan watersheds versus estimated values from eq 4. The regression of measured riverine TN exports with estimated riverine TN exports is similar to the 1:1 line (Measured TN_{export}=15.8 + 1.0 × Estimated TN_{export}, $R^2 = 0.87$).

observed F statistic (0.18) smaller than the critical value of F at the 5% level ($F_{12,75}$ =1.88, $p > 0.05$); thus, the second null hypothesis was not rejected. The Hausman statistic of 2.75 ($p = 0.0974 > 0.05$) does not reject the null hypothesis of unbiased random effects estimates at the 5% level, and so the random effect model is preferred to a fixed effects model. The resulting panel data regression using a random effects model in its original form is

$$\mathrm{RNEXPORT}_{it} = 11.65 \times Q_{it}^{0.46} \times \exp(3.49 \times 10^{-4} \times \mathrm{NANI}_{it}) \quad (4)$$

This model accounted for 87% of the variation in annual TN fluxes across all 18 watersheds over the five census years (Figure 3). All terms were statistically significant ($p < 0.001$) with a root-mean-square error of 167.4 kg-N km^{-2} yr^{-1} and the slope of the regression of measured against predicted river export exactly matched the 1:1 line.

Median errors of prediction accuracy for individual years were all less than 5%, and the interquartile range of each year was relatively symmetrical, typically ranging from ∼−15% to +15%, although a tendency for overprediction was noted for 1974 (Table S5, Supporting Information). The greatest variability and bias in prediction errors were observed when the model was used to predict the historical change in riverine TN exports for each watershed rather than spatial distribution across watersheds for each year.

Forecasting Future N Inputs and Exports. Estimated total NANI loading to the 18 Lake Michigan watersheds was ∼236 018 Mg-N/yr in 1997 and ∼217 478 Mg-N/yr in 2002. The status-quo scenario projects a modest 8% increase in anthropogenic N inputs to the 18 Lake Michigan Basin watersheds from ∼234 044 Mg-N/yr at the baseline to ∼253 607 Mg-N/yr in 2020. This increase results from greater import of N in food for an increased human population.

Under the organic scenario future N inputs (∼222 105 Mg-N/yr) would be 14% less than the status quo due primarily to decreases in fertilizer use and crop fixation resulting from decreased soybean acreage and an expected lower fixation rate due to high N availability resulting from intensive manure produced by grazing livestock. A reduction in the net export of N in food and feed (to ∼57 766 Mg−N/yr compared with ∼79 781 Mg−N/yr in the status quo scenario) due to increased demand of N by human and livestock, but less crop N production would partly offset decreases in other N inputs.

Under the third scenario of expanded corn-based ethanol production N inputs will increase markedly to 269 100 Mg-N/yr in 2020, ∼ 6% and ∼21% higher than under the status-quo and the organic scenarios, respectively. This is the consequence of intensive conventional agriculture based on heavy fertilizer use. After adjusting for projected increases in corn and wheat and decreases in soybean acreages based on the USDA projection (*23*) future fertilizer inputs are expected to increase by 12% in scenario 3. Net export of N in food and feed will increase due mainly to reduced livestock population, hence decreasing animal N consumption, and also because of increased crop N production.

Applying eq 4 to each of the three land management scenarios and two climate scenarios predicted a decrease of future N export under the organic scenario of 9% and 7%, respectively, for 5% and 10% increases in discharge relative to the average exports for census years 1974−1992 (Figure S5, Supporting Information). In contrast, the status-quo scenario predicts increases of 11% and 13%, and the biofuel scenario predicts increases of 21% and 24% by 2020, respectively, for 5% and 10% increases in discharge.

Discussion

This study develops a model incorporating both spatial and temporal variability to predict riverine N export based on anthropogenic N inputs and river discharge and applies this model to forecast future loadings and riverine TN export under different land use and climate scenarios for the Lake Michigan basin. We find that NANI is a better predictor of spatial variation in river export (Table S3, Supporting Information), whereas annual water discharge is a better predictor of temporal variation for individual watersheds (Table S4, Supporting Information). In addition, the spatial relationship between NANI and riverine TN exports varies by year as a function of annual water discharge (Figure S3a, Supporting Information) and precipitation (Figure S3b, Supporting Information).

Our model is similar in form to that for the Mississippi Basin (*2*), which also found that riverine nitrate fluxes increased exponentially with net anthropogenic N input and as a power function of annual water discharge. Our study suggests that variation in predicted TN exports is governed more by changes in NANI than by changes in discharge (Figure S4a, Supporting Information). In response to a 7-fold increase in NANI, from 1000 to 7000 kg-N km^{-2} yr^{-1}, riverine TN exports increase about 8-fold; in contrast, a 7-fold increase in water discharge results in approximately a doubling of TN export (Figure S4b vs S4c, Supporting Information).

According to eq 4 the amount of TN exported when NANI is zero is estimated to be $11.65 Q_{it}^{0.46}$, which implies that the amount of N exported from a watershed that receives only natural inputs varies among years as a function of discharge. We also found that discharge and precipitation accounted for a higher fraction of temporal variation in riverine TN exports for watersheds with <10% disturbed land based on simple linear regressions. Howarth et al. (*4*) considered the intercept value (107 kg-N km^{-2} yr^{-1}) of the linear regression between NANI and river TN exports for watersheds of the northeastern United States to represent a background N export from pristine watersheds. Our results suggest a background N export for Lake Michigan Basin tributaries in the vicinity from ∼150 (at an average water discharge of 268 mm/yr) to ∼180 kg-N km^{-2} yr^{-1} (at a discharge of 385 mm/yr) with the value varying among years as a function of discharge. Riverine TN exports have been shown to vary with annual discharge in a number of studies, including minimally disturbed watersheds of the American tropics (*29*) and for United States temperate watersheds (*3*).

This dependency on discharge of the relationship between N exports and watershed N inputs can be explained by two mechanisms. TN exports may be greater at high discharge because N sinks are smaller under wet conditions (*4*).

Reduced contact time between water and benthic sediments in low-order streams, wetlands, and riparian zones at high precipitation and discharge is expected to result in lower rates of in-stream denitrification and offset any increase in in-field denitrification rates that would be promoted by low-oxygen conditions associated with soils saturated by rainfall or irrigation (*30*). Additionally, even in wet conditions that favor in-field denitrification the presence of agricultural drainage tiles can reduce anoxic conditions by reducing the extent and duration of water saturation of soils (*31*). Other studies have reported that the percentage of aquatic N lost via denitrification and settling is greater at lower discharge due to increased settling of organic particulate nitrogen (*32*) as well as greater nitrate diffusion to benthic sediments and thus benthic denitrification (*33, 34*).

A possible alternative mechanism for variation in N exports between wet and dry years involves the flushing of N that accumulates during dry years and is exported in wet years (*2, 30*). Increased hydrologic responsiveness of N exports at high discharge in small urbanized watersheds can be explained by a "build and flush" model in which N accumulates on the surface of mostly impervious land and then is flushed by a rain event into streams (*35*). Fractional export of nitrate from Baltimore-area watersheds exhibited declines in a drought year and highest values in wet years across a range of land uses (*10*). This is a plausible contributing explanation for the smaller and more urbanized Lake Michigan Basin watersheds but is less likely to apply widely to our study system.

Among the several forecasts of future N inputs from river catchments into Lake Michigan the greatest delivery of N by rivers is seen at higher discharge and under the biofuel scenario, as expected. These results are consistent with recent estimates of a 10−34% increase in dissolved inorganic nitrogen exported to the Gulf of Mexico (*36*) and a 37% increase in nitrogen loss to water nationally (*37*) under scenarios designed to meet the increased ethanol demand. While nitrogen is not the primary limiting nutrient in Lake Michigan, our analysis of factors controlling nitrogen export from Lake Michigan watersheds provides important insights and potential predictive power for other regions as well. Although the projections of our model are subject to the uncertainties of future N inputs and water discharge, our results suggest that future N loadings to Lake Michigan would decrease under the organic scenario and increase under intensive bioethanol production and differences would be most pronounced in wet years. They are also consistent with analyses suggesting that changes in climate alone will increase loads to the Gulf of Mexico along with subsequent increased areas of oxygen depletion (*38*).

In comparison to some other models including Swat (*39*) and Sparrow (*40*) our approach using annual values for NANI and discharge lacks the ability to predict seasonal or daily river export and differentiate among possible fates of N within a watershed. However, it has the advantage of simplicity and can easily be applied to large, mixed-use watersheds and various scenarios. By incorporating temporal as well as spatial variation it also provides further insight into how the relationship between N inputs and exports can vary across years of differing discharge.

Acknowledgments

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Supporting Information Available

Text describing sources of relevant data used for NANI budgeting, NANI budgeting methods, explanation of panel data regression methods and performance of the panel regression model, error analysis and forecasting scenarios for watershed N input and river export; Tables of site descriptions, annual water discharge and precipitation of 18 Lake Michigan watersheds for five census years, the performances of the simple linear regressions using NANI, individual N inputs, and climatic variables to account for spatial and temporal variations in riverine TN exports, and evaluation of model accuracy; Figures of flowchart for developing a panel data regression model, the relative importance of individual N inputs across the 18 watersheds, three-dimensional contour map of simulated TN exports from the panel regression model, and forecasting of river N exports for the combined 18 Lake Michigan watersheds based on three scenarios of future N inputs and two climate scenarios. This material is available free of charge via the Internet at http://pubs.acs.org.

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