*Limnol. Oceanogr.*, 52(2), 2007, 856–861


# How climate controls the flux of nitrogen by the Mississippi River and the development of hypoxia in the Gulf of Mexico

*Simon D. Donner*
Woodrow Wilson School of Public and International Affairs, Princeton University, 447 Robertson Hall, Princeton, New Jersey 08544

*Donald Scavia*
School of Natural Resources and Environment, University of Michigan, 444 Church St., Ann Arbor, Michigan 48109

*Abstract*

The intensification of agriculture in the central U.S. is commonly cited as the primary cause of the increase in nitrogen (N) flux by the Mississippi River since the 1950s and the development of seasonal bottom-water hypoxia in the northern Gulf of Mexico. Over the past two decades, however, agricultural land use and land cover have remained relatively constant. With high N inputs each year, climate variability could now be controlling the variability in N leaching from land and transport through the river system. In this study, we examine how precipitation in specific regions of the central U.S. affects the nitrate–N flux by the Mississippi River and the extent of hypoxia in the Gulf of Mexico. Precipitation amounts across the Corn Belt in the previous November–December and in March–April–May are together a strong predictor ($r^2 = 0.68$) of the spring nitrate flux by the Mississippi. A hypoxia model shows that the year-to-year variability in central U.S. climate must be considered in developing nutrient management policy. During a wet year, an N reduction of 50–60%—close to twice the recommended target—is required to meet the goal of reducing the hypoxia zone to less than 5,000 km$^2$ in size. A higher reduction goal is particularly important considering the expected changes in climate in the coming decades.

Each summer, an area of hypoxic bottom water develops on the continental shelf of the northern Gulf of Mexico, near the outlet of the Mississippi River (Rabalais et al. 2002). This area of low oxygen concentration is a consequence of water column stratification and high primary production promoted by the input of freshwater and nutrients from the Mississippi River basin. The creation and expansion of this hypoxic zone was driven by the increased flux of agriculturally derived nitrogen (N) from the Mississippi Basin since the 1950s (Turner and Rabalais 1994; Goolsby and Battaglin 2001; Rabalais et al. 2002). The increase in N flux between the 1960s and 1990s has been specifically attributed to increased rates of fertilizer application on corn in the central U.S., increased cultivation of N-fixing soybeans, and a climate-driven increase in runoff (Donner et al. 2004*a*). The drainage of wetlands and installation of artificial drainage systems likely exacerbated N losses from central U.S. croplands in recent decades (Zucker and Brown 1998; Mitsch et al. 2001).

The areas of the major crops like corn (Donner 2003), the rates of fertilizer application (Donner et al. 2004*a*), and the drainage of wetlands (Zucker and Brown 1998; Dahl 2000) have remained relatively stable since the 1980s, in contrast to the changes of the previous decades. The factor that has varied the most in the past 25 yr is climate. Annual precipitation in the Mississippi River basin varied from a low of 817 mm in 1988 to a high of 1,207 mm in 1993 (CRU TS2.1 data; Mitchell and Jones 2005). The timing and amount of precipitation influences both the leaching of N, largely in the form of highly soluble nitrate, from land (Randall and Mulla 2001; Donner and Kucharik 2003) and the fraction of leached N that is transported downstream (Donner et al. 2004*b*). As a result, there is a strong relationship between the interannual variability in Mississippi River discharge and nitrate flux (McIssac et al. 2001; Donner et al. 2002; Justic et al. 2003*a*).

The runoff-driven variability in N flux is a primary cause of recent year-to-year variability in the size of the hypoxic region (Fig. 1), although variability in oceanographic conditions also plays an important role (Rabalais et al.

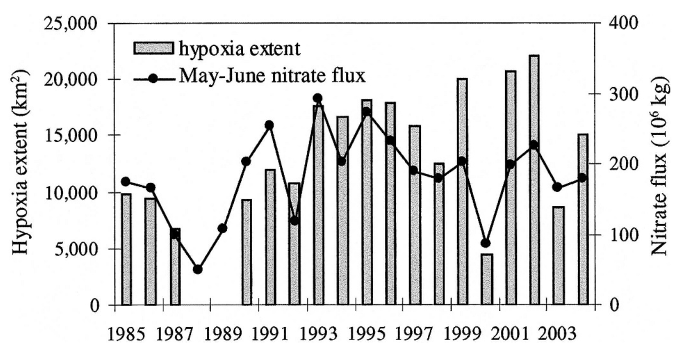


Fig. 1. M–J nitrate flux by the Mississippi River (at St. Francisville, Louisiana) and extent of seasonal hypoxia in the Gulf of Mexico between 1985 and the present. The hypoxic zone reached 40 km$^2$ in 1988; no data is available for 1989.

*Acknowledgments*

We thank Nancy Rabalais for providing the hypoxia data and two anonymous reviewers for comments on the manuscript. The research was made possible through the generous support of the High Meadows Leadership and Policy Fund, Princeton University's Co-operative Institute for Climate Studies and the University of Michigan School of Natural Resources and Environment.

2002; Scavia et al. 2003; Turner et al. 2005). The most extreme example is the difference between the 1988 drought, when the hypoxic zone reached only 40 $km^2$ in size, and the 1993 flood, when the hypoxic zone grew to cover 17,000 $km^2$ (Rabalais pers. comm.). With less dramatic year-to-year change in land use and land cover, the question is to what degree is the extent of hypoxia now determined by the weather in the heavily cultivated central U.S.

Here, we use an understanding of the sources of Mississippi River N gained from previous modeling studies to determine how precipitation influences the flux of nitrate from the Mississippi River basin and the extent of summer hypoxia. We then explore the potential for weather-based forecasting of spring nitrate flux and the extent of hypoxia. The results provide insight into the impact of climate change on Mississippi N flux and the development of suitable policy to meet the hypoxia reduction goal for the Gulf of Mexico.

## Methods and data sources

Long-term observations of precipitation, Mississippi River discharge, Mississippi River nitrate–N flux, and the extent of midsummer seasonal hypoxia are used in this analysis. Monthly mean precipitation data are derived from the $0.5^\circ \times 0.5^\circ$ ($\sim$42–54 km) spatial resolution global data set for 1901–2002 (known as CRU TS2.1) developed by the Climate Research Unit of the University of East Anglia (Mitchell and Jones 2005). Spatially averaged precipitation for the Mississippi Basin and subregions is determined using the historical data and a $5' \times 5'$ ($\sim$7 $\times$ 9-km) resolution drainage map (Donner et al. 2002). Precipitation data are expressed in water years, a water year being the period from the previous July to June.

The mean monthly discharge and nitrate flux for the Mississippi River are based on U.S. Geological Survey data for St. Francisville, Louisiana, the station closest to the mouth of the river, which has records dating from 1955 (USGS 2005). The Mississippi River basin discharges to the Gulf of Mexico through the Mississippi River and the neighboring Atchafalaya River. The Old River diversion, just upstream of St. Francisville, diverts 30% of the combined flow of the Mississippi and Red Rivers into the Atchafalaya River (USGS 2005). The discharge and flux of the Atchafalaya is excluded from the flux-estimation part of this study because the available data record is shorter (since 1979) and the N flux at St. Francisville is a strong proxy for the total flux from the combined river system ($r^2 = 0.98$, between 1979 and 2004).

Data on the extent of midsummer bottom-water hypoxia on the continental shelf of the northern Gulf of Mexico are taken from the annual surveys conducted by the Louisiana Universities Marine Consortium since 1985 (Rabalais unpubl. data). The hypoxic zone typically stretches westward from the Mississippi Delta towards Texas because of prevailing circulation in the Gulf of Mexico. The extent of hypoxia (in $km^2$) represents the total area of bottom waters with dissolved oxygen levels $<2$ mg $L^{-1}$, extrapolated from point field measurements.

This study focuses on the predictors of late spring (May + June) flux of nitrate. River discharge and nitrate flux by the Mississippi River typically peaks during late spring because of the drainage of spring rains and late winter snowmelt in the northern part of the basin. The spring flux fuels primary production on the continental shelf and leads to the development of summer bottom-water hypoxia (Turner et al. 2005). Between 1985 and 2004, there is a significant relationship ($r^2 = 0.61$) between midsummer hypoxia area and the May + June nitrate flux (Fig. 1). The strength of this relationship is limited by a number of other variables, including the advection of sub-pycnoclinal waters on the continental shelf, summer tropical storms that increase vertical mixing, recycling of N sequestered in shelf sediments during previous years, and the input of other nutrients such as phosphorus (Rabalais et al. 2002; Scavia et al. 2003; Wawrik et al. 2004).

## Climate and nitrate flux by the Mississippi

We examined the relationship between the May–June nitrate flux (referred to as M–J flux) and precipitation in the portion of the 3.2 million–$km^2$ Mississippi Basin where the majority of N is believed to currently originate. Several studies have concluded that the heavily cultivated Corn Belt, an area of land stretching from Nebraska eastward to Ohio, is currently responsible for the majority of N reaching the Gulf of Mexico (e.g., Goolsby and Battaglin 2001; Donner et al. 2004*a*). We defined an N source region (roughly 97–83°W, 38–43°N) using the spatial pattern in annual mean dissolved inorganic N (DIN) leaching from land estimated by Donner et al. (2004*a*) for the 1985–1994 period (Fig. 2). Despite representing less than 20% of the Mississippi Basin, this region features over 60% of the basin's corn and soybean cultivation and is responsible for over 60% of DIN leaching to the river system (Donner et al. 2004*a*). The annual precipitation in the source region (961 mm $yr^{-1}$) is 19% higher than the mean for the Mississippi Basin and also exhibits greater annual variability (coefficient of variation of 0.12 vs. 0.09 for the Mississippi Basin mean). We focus primarily on the period since 1980, during which fertilizer application, crop distribution, and drainage were more stable relative to the dramatic changes in the previous decades.

Regression analysis indicates that there is an approximately linear relationship between M–J flux and precipitation over the N source region during a portion of the previous water year. The linear fit agrees with observations of hysteresis in solute concentrations in streams; for further explanation, see Web Appendix 1 (http://www.aslo.org/lo/toc/vol_52/issue_2/0856a1.pdf). The precipitation over the entire water year explains 57% of the variability ($r^2 = 0.57$) in M–J flux from 1980 to 2002 ($p < 0.01$, RSME = 25% of annual mean M–J flux). The relationship becomes stronger when only the November–May precipitation is used in the regression ($r^2 = 0.64$). Substituting the precipitation in the N source region with that of the entire Mississippi Basin does not improve the regression. A weaker relationship ($r^2 = 0.41$ for November–May precipitation) can be detected back to 1960, if the increasing trend is removed from the

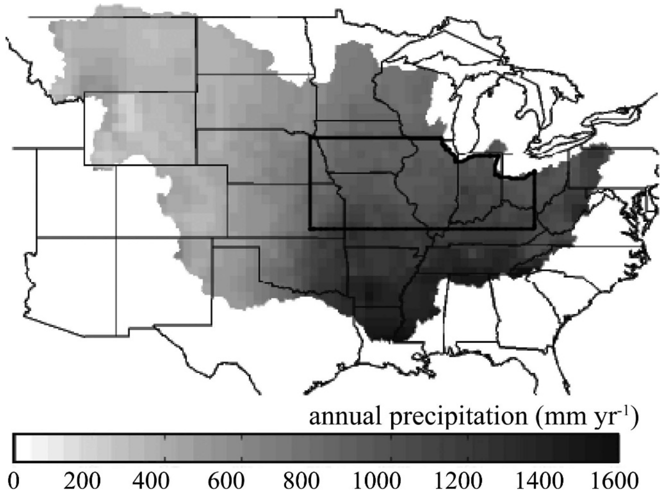


Fig. 2. Mean annual precipitation across the Mississippi River basin for 1980–2002. The black line delineates the border of the N source region employed in this study.

M–J flux time series. The de-trended relationship is less coherent because the sources of N were distributed more broadly across the Mississippi Basin in the 1960s and 1970s (Donner et al. 2004*a*), and the disruption of natural drainage, via the destruction of riparian wetlands and installation of tile drains, since then may have enhanced the response of terrestrial N leaching and river N flux to rainfall.

The relationship between precipitation in the source region and M–J flux is strongest when the influences of the fall weather and the spring weather are considered separately. A multiple linear regression of November–December (N–D) and March–May (M–M) precipitation explains 70% of the variability in M–J flux from 1980 to 2000 (Fig. 3). The influence of N–D precipitation on M–J flux is not a result of autocorrelation with M–M precipitation; there is no correlation between M–M and N–D precipitation ($r^2 < 0.01$). The regression implies that M–M precipitation has twice as much influence on M–J flux as N–D precipitation.

The simple linear regression roughly captures the primary processes—fall soil recharge, late winter snowmelt, and spring rains—influencing the spring runoff and nitrate flux in the N source region. In November and December, precipitation exceeds evapotranspiration, leading to soil recharge. The soil moisture conditions and the M–M precipitation then determine the level of spring runoff and nitrate flux. Antecedent soil moisture is a stronger predictor of M–M runoff in the central U.S. than winter snow depths (Maurer and Lettenmaier 2003), which explains why the January and February precipitation have a negligible influence on prediction of the M–J flux. The remaining variance in the nitrate flux time series since 1980 is because of factors like changes in soybean cultivation, continuing installation of artificial drainage, and the influence of air temperature on N cycling and evapotranspiration.

Comparison of individual years in the time series demonstrates the influence of both N–D precipitation or soil recharge and M–M precipitation on M–J flux. For

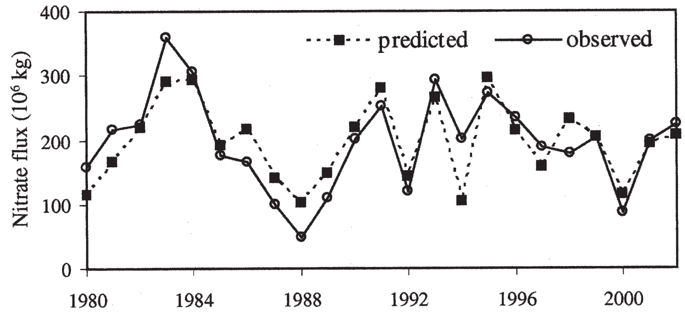


Fig. 3. Predicted and observed M–J nitrate flux by the Mississippi River at St. Francisville, Louisiana, from 1980 to 2002.

example, the M–M precipitation was similar (323–346 mm) during the water years of 1982–1983 and 1989–1990. The M–J flux was 83% higher than average in 1983, but only 3% higher than average in 1990. The difference was the N–D precipitation and soil recharge: N–D precipitation was the highest in the time series (219 mm) in 1982–1983, but the lowest in two decades (51 mm) in 1989–1990.

The dependence of Mississippi River nitrate flux on precipitation in a climatically distinct subregion of the Mississippi Basin, rather than the basin as a whole, raises the possibility for a weather-based hypoxia forecast. If the central U.S. experiences a wet November and December, a seasonal forecast for a wet spring would imply a high M–J nitrate flux and a high probability for extensive development of hypoxia on the continental shelf. The ability to make a precise ecological forecast is currently limited by the skill of long-lead weather forecasts for the central U.S. But some insight can be gained from the North Atlantic Oscillation (NAO) and the El Niño/Southern Oscillation (ENSO), which influence moisture advection into the central U.S. (Ropelewski and Halpert 1986; Trenberth and Guillemont 1996; Bates et al. 2001). The concurrence of the ENSO events and the positive phase of the NAO, as occurred in 1973, 1983, and 1993, usually causes an extremely wet spring. For example, in January of 1993, after two months of high rainfall in the central U.S., a forecast based on the climate indices would have predicted a high probability for an anomalously large spring nitrate flux and hypoxic zone. An advance hypoxia forecast currently has little practical application, but may eventually prove instructive to upstream N management or to the direction of fisheries effort in the Gulf.

## N flux and the extent of hypoxia

The influence of central U.S. precipitation on Mississippi nitrate flux implies the possibility of a relationship between central U.S. precipitation and the extent of summer hypoxia in the Gulf of Mexico. The N–D and M–M precipitation are alone not strong predictors of the extent of summer hypoxia ($r^2 = 0.27$, $p < 0.12$, for 1985–2002). The rainfall–hypoxia relationship can be improved by including the previous year's nitrate flux as a rough proxy for N stored in shelf sediments during the previous year. A model using both the precipitation and the nitrate flux from the previous spring and summer (May–August) is a stronger

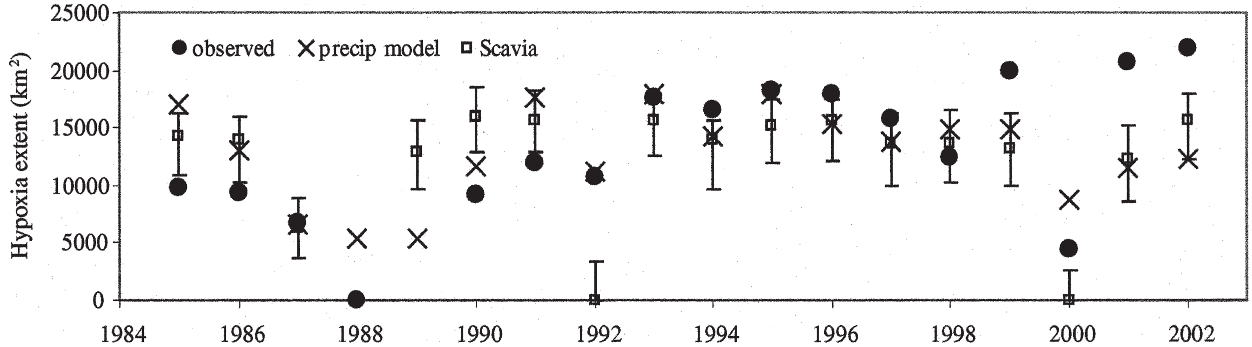


Fig. 4. Predicted and observed extent of seasonal hypoxia from 1985 to 2002. Scavia refers to the result from Scavia et al. (1993); error bars represent the range between the results for first and third quartiles. The model predicts no hypoxic zone in 1988 and 1994. The precipitation model is based on the N–D precipitation, the M–M precipitation, and the previous year's May–August nitrate flux.

predictor of the extent of summer hypoxia ($r^2 = 0.37$, $p < 0.04$). This correlation reflects how the "memory" of a high nitrate flux can influence the growth of the hypoxic zone the subsequent year (Turner et al. 2005).

A more robust estimate of the effects of basin precipitation on hypoxia development can be made with the simple biophysical model of Scavia et al. (2003). The biophysical model calculates the dissolved oxygen deficit based on bottom-water oxygen demand driven by N inputs. A distribution of the areal extent of the hypoxia is estimated with constant reaeration and decay coefficients and a Monte Carlo analysis using randomly assigned values for downstream advection of sub-pycnoclinal waters (Scavia et al. 2003). The biophysical model, and, to a lesser degree, the precipitation-based model can explain much of the variability in the areal extent of hypoxia (Fig. 4). The predictive ability of such simple models confirms the central role of climate-driven variability in M–J flux on the annual development of hypoxia. If the central U.S. experiences high N–D and M–M precipitation, or average N–D and M–M precipitation following a year with high nitrate flux, and there are favorable oceanographic conditions, there will be extensive hypoxia in the Gulf of Mexico.

The year-to-year variability in precipitation and ocean conditions complicates the setting of nutrient reduction targets to minimize the extent of hypoxia. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force Action Plan (referred to as the Action Plan) suggested that the mean N flux from the Mississippi Basin would have to be reduced by 30% to reach the goal of reducing the 5-year running average of the areal extent of hypoxia to less than 5,000 km$^2$ (plan available at: http://www.epa.gov/msbasin/taskforce/actionplan.htm). Ensemble forecasts by Scavia et al. (2003) showed that a 40–45% reduction in mean N flux would be necessary to meet the hypoxia goal in most years because of the variability in ocean conditions. The precipitation–flux relationship described here implies that an even larger percentage reduction may be required in wet years to reach that N flux target. For example, to have achieved the stated N flux target for M–J (e.g., $2.3 \times 10^6$ kg day$^{-1}$, 30% less than the 1980–2002 mean), the actual reduction would need to have been over 50% in the wet years of 1983, 1984, 1993, and 1995.

We can evaluate the choice of N reduction targets in light of uncertainty in both climate and ocean conditions by integrating the biophysical model and the precipitation–flux relationship. Analysis of central U.S. precipitation between 1901 and 2000 indicates the climate-driven coefficient of variation of nitrate flux to be 33%. We use the coefficient of variation to calculate the upper and lower bounds in annual N flux for each mean N flux reduction. This can also be interpreted in terms of N concentration: the precipitation–flux model implies that, for a given set of land cover and land use practices, the spring river N concentration remains roughly constant from year to year. A percentage reduction in N concentration, caused by a nutrient policy altering land cover, land use, or drainage practices, produces a range of actual N flux depending on the precipitation each year.

The results demonstrate that the N reduction target should be sensitive to the effect of precipitation-driven variability in N flux by the Mississippi (Fig. 5). The individual effect of climate variability on hypoxia development is greater than the effect of variability in ocean conditions found by Scavia et al. (2003). In dry years, the models indicate that there should be little concern about development of hypoxia. This is confirmed by the absence of hypoxia in 1988. In wet years, however, an N reduction target of 50–60% would be necessary to meet the hypoxia goal, given the possible range of ocean conditions.

Justic et al. (2003*b*, 2005) reach a similar conclusion using a two-layer model for one location in the hypoxic region. Although their model is not designed to simulate the areal extent of hypoxia, it did show that a climate-related increase in river N load would increase the frequency of years in which the bottom layer of water in their model becomes hypoxic. In their analysis, a 20% increase in N load resulted in a 37% increase in the frequency of hypoxic conditions over the 1955–2000 simulation period. It is not possible to compare the results of that study directly with our findings; the studies do all support the conclusion that the climate-driven variability in nitrate flux must be incorporated into nutrient management policy. Here, the inclusion of precipitation-driven variability in N export by the Mississippi as well as the variability in ocean conditions show that the reduction

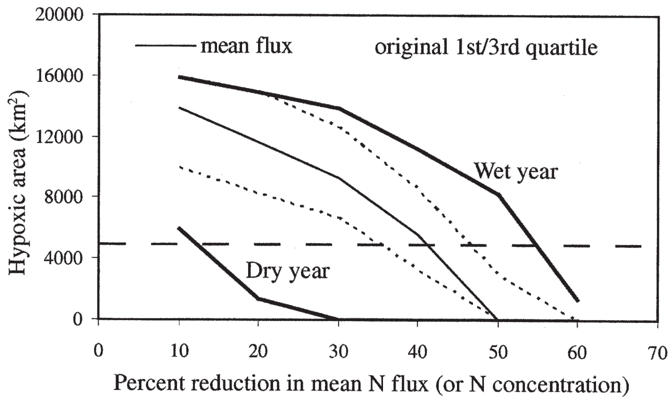


Fig. 5. Ensemble forecasts of the response of hypoxia to reductions in mean N flux (or N concentration). The dashed line represents the forecast from Scavia et al. (2003) reflecting variability in ocean conditions. The solid line represents the lower (dry year) and upper (wet year) bounds based on central U.S. precipitation variability. The horizontal dashed line at 5,000 km$^2$ is the target set by the Action Plan.

target may need to be higher than that in the Action Plan (30%) or the Scavia et al. (2003) model (40–45%), which considered only the variability in ocean conditions.

## Implications

The influence of central U.S. precipitation on nitrate flux by the Mississippi highlights a key shortcoming of the N load reduction target suggested by the Action Plan. This target fails to account for how the input of freshwater, the input of nutrients, and the development of hypoxia vary with climatic and oceanographic conditions. A higher reduction goal is particularly important given the projections for future changes in climate in the coming decades. The acceleration of the hydrologic cycle, as suggested by recent climate trends and general circulation model (GCM) predictions, would lead to an increase in wet and dry spells, the intensity of rainfall events, and the frequency of large floods (Karl and Knight 1998; Milly et al. 2002, 2005).

Explicit simulation of future variability in N flux and hypoxia is difficult because of substantial disagreement in forecasts of mid-continental precipitation and runoff between the different atmosphere–ocean GCMs used in future climate assessments (Wolock and McCabe 1999; Milly et al. 2005). Instead, we can gain some insight on the influence of long-term climate variability and change on N flux by examining the climate of the 20th century. The last three decades of the 20th century were the three wettest of the century in the central U.S.; the N–D and M–M precipitation were 24% and 5% greater, respectively, than the mean for the previous 70 yr. If current land use and land cover in the central U.S. had been applied throughout the 20th century, the precipitation relationship in this study implies that the 1970–1999 period would have experienced a mean M–J flux 11% above average and 7 of the top 10 M–J flux events of the century.

The late–20th-century trend presents a cautionary tale for nutrient management policy in a changing climate with an accelerated hydrologic cycle. For example, if a continued increase in precipitation causes a further 11% increase in the mean M–J flux in the next 30 yr, just reaching the established N flux target (30% less than the 1980–2000 mean) would require a 36% reduction in the M–J flux. Even with no increase in the year-to-year variability in central U.S. precipitation, a reduction target of at least 55% will be necessary to reduce the hypoxic zone to less than 5,000 km$^2$ in many years.

Reaching such a goal may be impossible without a dramatic reduction in agricultural N inputs through a shift in food production or diets (Donner 2006) and an extensive wetland restoration program in the central U.S. designed to optimize the removal of agriculturally derived N via denitrification (Crumpton 2001; Mitsch et al. 2001; Hey 2002). Partial restoration of the natural drainage system, disrupted by the installation of drainage tiles, the destruction of riparian wetlands, the channelization of rivers, and the destruction of Gulf Coast wetlands, could help decrease the response of nitrate flux to precipitation. Without substantial changes to the landscape or to N inputs in the central U.S., the extent of the Gulf of Mexico hypoxic zone each year will continue to be controlled by the climate.

## *References*


Bates, G. T., M. P. Hoerling, and A. Kumar. 2001. Central U.S. springtime precipitation extremes: Teleconnections and relationships with sea surface temperature. J. Clim. **14:** 3751–3766.

Crumpton, W. G. 2001. Using wetlands for water quality improvement in agricultural watersheds; the importance of a watershed scale approach. Water Sci. Technol. **44:** 559–564.

Dahl, T. E. 2000. Status and trends of wetlands in the conterminous United States 1986 to 1997. U.S. Department of the Interior, Fish and Wildlife Service.

Donner, S. D. 2003. The impact of cropland cover on river nutrient levels in the Mississippi River basin. Glob. Ecol. Biogeogr. **12:** 341–355.

———. In press. Surf or turf: A shift from feed to food cultivation could reduce nutrient flux to the Gulf of Mexico. Glob. Environ. Change. doi: 10.1016/j.glovencha.2006.04.005.

———, M. T. Coe, J. D. Lenters, T. E. Twine, and J. A. Foley. 2002. Modeling the impact of hydrological changes on nitrate transport in the Mississippi River basin from 1955–1994. Glob. Biogeochem. Cycles **16**, doi:10.1029/2001GB00139.

———, and C. J. Kucharik. 2003. Evaluating the impacts of land management and climate variability on crop production and nitrate export across the Upper Mississippi Basin. Glob. Biogeochem. Cycles **17**, doi:101028/2001GB1808.

———, ———, and J. A. Foley. 2004*a*. The impact of changing land use practices on nitrate export by the Mississippi Basin. Glob. Biogeochem. Cycles **18**, doi:10.1029/2003GB002093.

———, ———, and M. Oppenheimer. 2004*b*. The influence of climate on in-stream removal of nitrogen. Geophys. Res. Lett. **31**, doi:10.1029/2004GL020477.

Goolsby, D. A., and W. A. Battaglin. 2001. Long-term changes in concentrations and flux of nitrogen in the Mississippi River Basin, USA. Hydrol. Process. **15:** 1209–1226.

Hey, D. L. 2002. Nitrogen farming: Harvesting a different crop. Restor. Ecol. **10:** 1–10.

Justic, D., N. R. Rabalais, and R. E. Turner. 2003*a*. Simulated responses of the Gulf of Mexico hypoxia to variations in climate and anthropogenic nutrient loading. J. Mar. Syst. **42:** 115–126.

———, R. E. Turner, and N. N. Rabalais. 2003*b*. Climatic influences on riverine nitrate flux: Implications for coastal marine eutrophication and hypoxia. Estuaries **26:** 1–11.

———, N. R. Rabalais, and R. E. Turner. 2005. Coupling between climate variability and coastal eutrophication: Evidence and outlook for the northern Gulf of Mexico. J. Sea Res. **54:** 25–35.

Karl, T. R., and R. W. Knight. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bull. Am. Meteorol. Soc. **79:** 231–241.

Maurer, E. P., and D. P. Lettenmaier. 2003. Predictability of seasonal runoff in the Mississippi River basin. J. Geophys. Res. Atmospheres **108**, doi:10.1029/2002JD002555.

McIssac, G. F., M. B. David, G. Z. Gertner, and D. A. Goolsby. 2001. Eutrophication: Nitrate flux in the Mississippi river. Nature **414:** 166–167.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia. 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature **438:** 347–350.

———, R. T. Wetherald, K. A. Dunne, and T. L. Delworth. 2002. Increasing risk of great floods in a changing climate. Nature **415:** 514–517.

Mitchell, T. D., and P. D. Jones. 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. **25:** 693–712.

Mitsch, W. J., J. W. Day, J. W. Gilliam, P. M. Groffman, D. L. Hey, G. W. Randall, and N. M. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to counter a persistent ecological problem. Bioscience **51:** 373–388.

Rabalais, N. N., R. E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. Bioscience **52:** 129–142.

Randall, G. W., and D. J. Mulla. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. J. Environ. Qual. **30:** 337–344.

Ropelewski, C. F., and M. S. Halpert. 1986. North American precipitation and temperature patterns associated with the El Nino-Southern Oscillation (ENSO). Mon. Weather Rev. **114:** 2352–2362.

Scavia, D., N. N. Rabalais, R. E. Turner, D. Justic, and W. J. Wiseman. 2003. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. Limnol. Oceanogr. **48:** 951–956.

Trenberth, K. E., and C. J. Guillemot. 1996. Physical processes involved in the 1988 drought and 1993 floods in North America. J. Clim. **9:** 1288–1298.

Turner, R. E., and N. N. Rabalais. 1994. Coastal eutrophication near the Mississippi river delta. Nature **368:** 619–621.

———, ———, and D. Justic. 2005. Predicting summer hypoxia in the northern Gulf of Mexico: riverine N, P, and Si loading. Mar. Pollut. Bull. **52:** 139–48.

U.S. Geological Survey (USGS). 2005. USGS nutrient loading and river discharge data [Internet]. [Accessed 2005 October] Available from http://toxics.usgs.gov/hypoxia/.

Wawrik, B., J. H. Paul, D. A. Bronk, D. John, and M. Gray. 2004. High rates of ammonium recycling drive phytoplankton productivity in the offshore Mississippi River plume found in the oligotrophic Gulf of Mexico. Aquat. Microb. Ecol. **35:** 175–184.

Wolock, D. M., and G. J. McCabe. 1999. Estimates of runoff using water-balance and atmospheric general circulation models. J. Am. Water Resour. Assoc. **35:** 1341–1350.

Zucker, L. A. and L. C. Brown. [eds.]. 1998. Agricultural drainage: Water quality impacts and subsurface drainage studies in the Midwest. Ohio State University Extension Bulletin 871.

*Received: 17 April 2006*
*Amended: 14 November 2006*
*Accepted: 19 October 2006*