REPORT

Legacy nitrogen may prevent achievement of water quality goals in the Gulf of Mexico

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Haunted by the past

Reducing the extent of hypoxia in the Gulf of Mexico will not be as easy as reducing agricultural nitrogen use. Van Meter *et al.* report that so much nitrogen from runoff has accumulated in the Mississippi River basin that, even if future agricultural nitrogen inputs are eliminated, it will still take 30 years to realize the 60% decrease in load needed to reduce eutrophication in the Gulf. This legacy effect means that a dramatic shift in land-use practices, which may not be compatible with current levels of agricultural production, will be needed to control hypoxia in the Gulf of Mexico.

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Abstract

In August 2017, the Gulf of Mexico's hypoxic zone was declared to be the largest ever measured. It has been estimated that a 60% decrease in watershed nitrogen (N) loading may be necessary to adequately reduce eutrophication in the Gulf. However, to date there has been no rigorous assessment of the effect of N legacies on achieving water quality goals. In this study, we show that even if agricultural N use became 100% efficient, it would take decades to meet target N loads due to legacy N within the Mississippi River basin. Our results suggest that both long-term commitment and large-scale changes in agricultural management practices will be necessary to decrease Mississippi N loads and to meet current goals for reducing the size of the Gulf hypoxic zone.

The areal extent of the northern Gulf of Mexico's hypoxic zone has been measured annually since 1985 and has varied in size from a 1988 minimum of <100 km^2 to the 22,729 km^2—larger than the state of New Jersey—observed in 2017 (*1*, *2*). Problems of hypoxia have been noted along the Louisiana continental shelf in the Gulf of Mexico since the 1970s, and the sediment record indicates that oxygen stress has increased in severity since the 1950s (*1*), parallel to increases in commercial fertilizer use across the Mississippi River basin (MRB) (*3*, *4*).

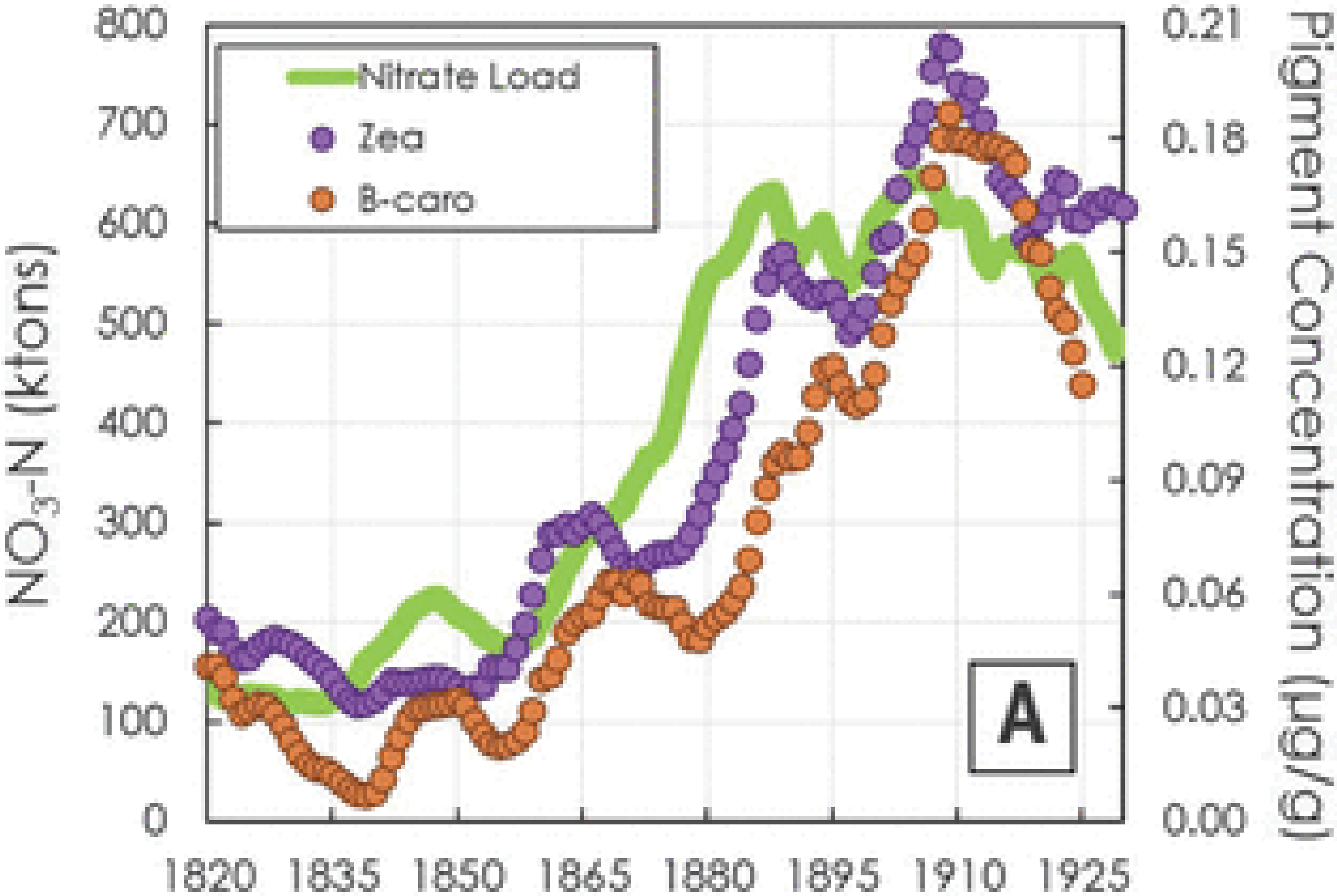
In 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (WNTF) developed an action plan to reduce hypoxia in the Gulf of Mexico and to protect inland waters. The WNTF's stated goal for the Gulf was to reduce the average area of the hypoxic zone to <5000 km^2 by 2015—a reduction that would require an estimated 60% decrease in nitrogen (N) loading from the Mississippi River (*5*, *6*). Since 2001, millions of dollars have been spent on a range of conservation measures across the MRB, including wetland restoration, construction of riparian buffers, planting of cover crops, and improved nutrient management, targeting both surface and subsurface pathways of N loss (*7*). However, despite such interventions, the hypoxic zone in 2015 was three times the size called for by the WNTF, and the target year has since been pushed to 2035.

Such a failure to meet water quality goals is not unique to the MRB. In the Chesapeake Bay region, for example, policy measures to reduce N loading have been in place since the 1990s, leading to improved nutrient management practices. Despite these efforts, annual N pollution to the Chesapeake Bay remains at more than 5000 kilotons above 2017 goals (*8*). Although there is further scope for implementation of conservation measures, one of the key causes of failures to reduce nutrient loading to surface waters is the existence of nutrient legacies within intensively managed watersheds (*9*). Such legacies, which we define as nutrients that remain within a watershed at least 1 year beyond their initial application at the land surface, exist within soil and groundwater and can serve as long-term sources to surface waters. As a result, current-year reductions in N use may have little effect on short-term changes in N loading at the catchment outlet. In other words, time lags in watershed response must be expected.

For the MRB, numerous modeling approaches have been used to identify the steps necessary to meet water quality goals for the Gulf. Most, however, do not adequately capture the legacy-related nonlinear relationships between N inputs and outputs typical of the problem of reducing N pollution to receiving water bodies (*10*). For example, many approaches rely on fixed, empirical relationships to estimate the landscape-to-stream delivery of nutrients, assuming that nutrients do not accumulate within the landscape (*11*–*16*). Although these relationships may be useful for characterizing spatially varying patterns in watershed dynamics, they are inherently unable to predict changes in loading over long time scales and under nonstationary management conditions (*17*, *18*). Indeed, even most mechanistic watershed models (*19*) do not satisfactorily consider the potentially long residence times for N within the subsurface and therefore do not allow us to account for the effects of N legacies on long-term nutrient loading.

In this study, we used the process-based ELEMeNT (Exploration of Long-tErM Nutrient Trajectories) model (*4*) to address the ways in which watershed legacy N may affect changes in N loading under major changes in land use and management. ELEMeNT was specifically designed to account for non–steady-state conditions under which N may accumulate in both soils and groundwater, thus capturing the “memory effects” of past nutrient management (see the supplementary materials for more detail). We used the ELEMeNT model to address two primary questions: (i) Is it possible to achieve the desired reductions in loading to the Gulf of Mexico within the specified time horizons? (ii) To what extent are sources of legacy N within the MRB hindering our attempts to reduce N loading?

We have previously used ELEMeNT to hindcast a >200-year trajectory of MRB nitrate loading (1800–2015) (*4*), with measured 1955–2013 N loading data being used for model calibration and validation (see supplementary materials). In this work, we used sediment core chloropigment data from the Gulf of Mexico to further cross-validate the ability of ELEMeNT to predict changes in N loading across periods of changing land use and management (*20*) (**Fig. 1**). Our analysis suggests strong linearity between model-predicted N loads and inferred primary productivity along the Gulf’s continental shelf during two key, dynamic periods of watershed history: (i) the period of European settlement and early watershed development (1820–1930), when pristine lands were being brought under cultivation at rates as high as 15,000 km^2/year, and (ii) from 1960 to 2000, when there was a greater than sixfold increase in commercial N fertilizer use (fig. S1).



Nitrate Load
Zea
B-caro
A
NO3-N (ktons)
Pigment Concentration (μg/g)
0
100
200
300
400
500
600
700
800
0.00
0.03
0.06
0.09
0.12
0.15
0.18
0.21
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1835
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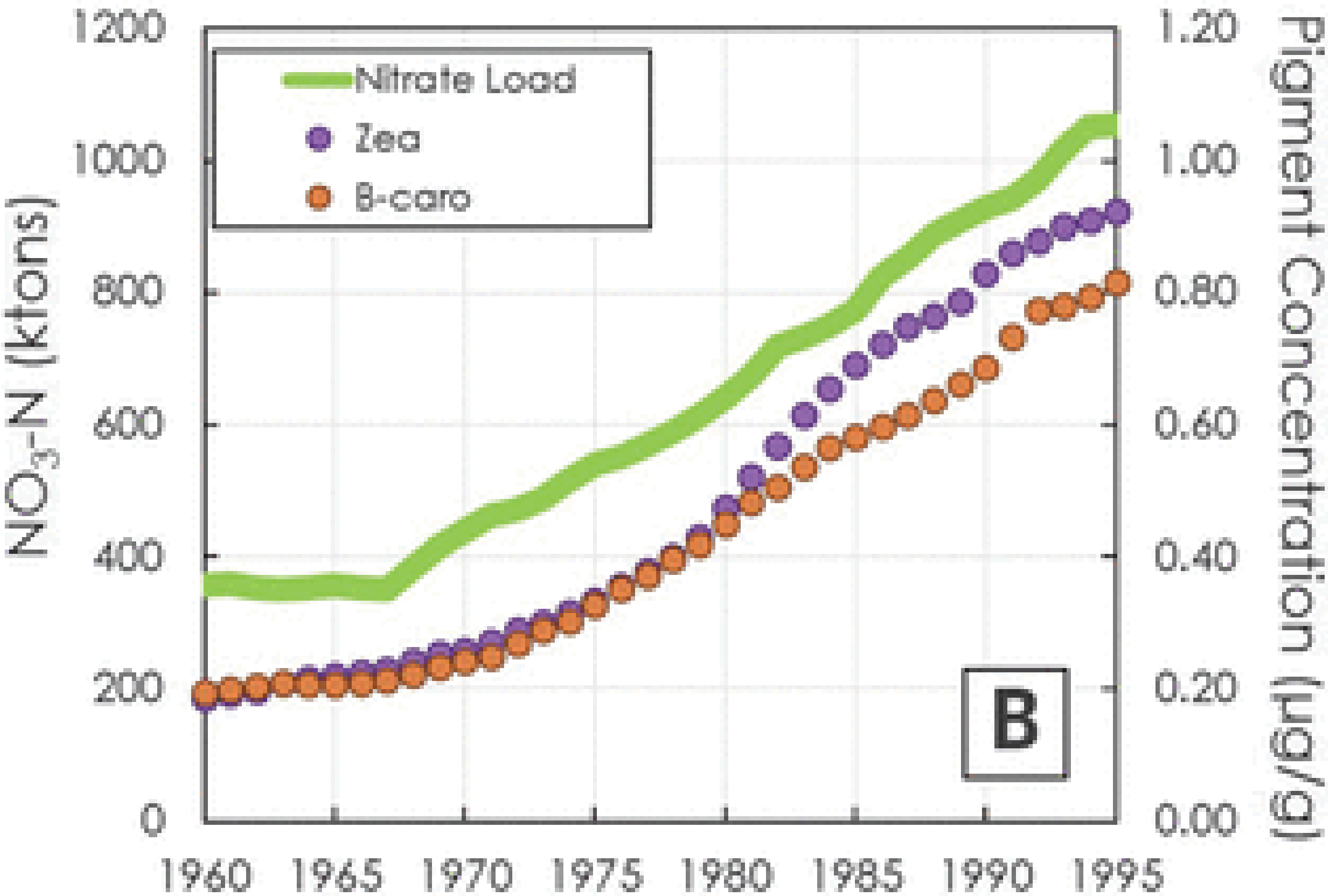

Nitrate Load
Zea
B-caro
B
NO3-N (ktons)
Pigment Concentration (μg/g)
0
200
400
600
800
1000
1200
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1960
1965
1970
1975
1980
1985
1990
1995

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Fig. 1 N loading trajectories at the MRB outlet compared to sediment core pigment concentrations.

The ELEMeNT model accurately predicts long-term trends in Mississippi nitrate loading, as demonstrated by the close relationship between the modeled annual loads (green line) and depth-varying chloropigment concentrations (purple and orange) within a sediment core obtained from the northern Gulf of Mexico (*20*). The panels represent two different periods of watershed land use: (**A**) European settlement and large-scale conversion of prairie lands to row crop (1820–1930) (zeaxanthin, coefficient of determination R^2 = 0.66, P < 0.001; β-carotene, R^2 = 0.57, P < 0.001) and (**B**) rapid 20th century increases in N fertilizer use (1960–2000) (zeaxanthin, R^2 = 0.0.86, P < 0.001; β-carotene, R^2 = 0.84, P < 0.001). Both chloropigments shown here (zeaxanthin and β-carotene) are known proxies of high phytoplankton biomass, with β-carotene being common to many types of algae and zeaxanthin being specifically associated with cyanobacteria. ktons, kilotons.

Next, to determine whether it is possible to achieve desired reductions in N loading within the time horizons specified by the policy goals, we used ELEMeNT to model multiple scenarios of future watershed management for the MRB. In the first scenario, we assumed business-as-usual (BAU) practices, meaning that cropping patterns, nutrient use, and livestock management remain the same (see supplementary materials) (*12*). For the other scenarios, we imposed instantaneous decreases (25%, 75%, and 100%) in the MRB-wide agricultural N surplus. In these scenarios, we focused on simple reductions in the N surplus, which was calculated as the difference between N inputs to cropland (in the form of fertilizer, livestock manure, and atmospheric N deposition) and N outputs (in the form of livestock and crop production). Such reductions were used as a means of representing a variety of possible changes in land use and management, ranging from moderate reductions in fertilizer use to fundamental changes in the agricultural production system, as might occur with widespread conversion from row-crop agriculture to the planting of perennial biofuel crops such as switchgrass and *Miscanthus* (*21*). Also, when evaluating the results of our simulations, we assumed, based on analysis of historical data (fig. S3), that reductions in stream N from NO_3 (hereafter, NO_3-N) loads linearly correlate with reductions in total N loads (see supplementary materials).

Our results show that by 2050, the modeled scenarios could result in NO_3-N loading reductions of anywhere from 11 to 55% of 1980–1996 values (**Fig. 2**). The BAU loading trajectory is particularly noteworthy because it suggests that, due to legacy N sources within the watershed, an 11% reduction in N loading could be achieved over the next four decades merely by maintaining the status quo. To come close to achieving the areal goal for the hypoxic zone, however, it would be necessary to bring the N surplus to zero, a change that would require 100% efficiency in agricultural N use. This 100% efficiency scenario is not only considered unrealistic but also inherently unsustainable, with researchers suggesting that, to avoid potential decreases in crop production and an increased risk of soil degradation, efficiency values should not exceed 90% (*22*). It is also important to note here not only the magnitude of the N surplus reduction necessary to achieve policy goals but also the time required to achieve the desired change. Under all of the management scenarios, from BAU to the 100% reduction, it takes more than 30 years for NO_3-N loading to reach new steady-state values (**Fig. 2**).

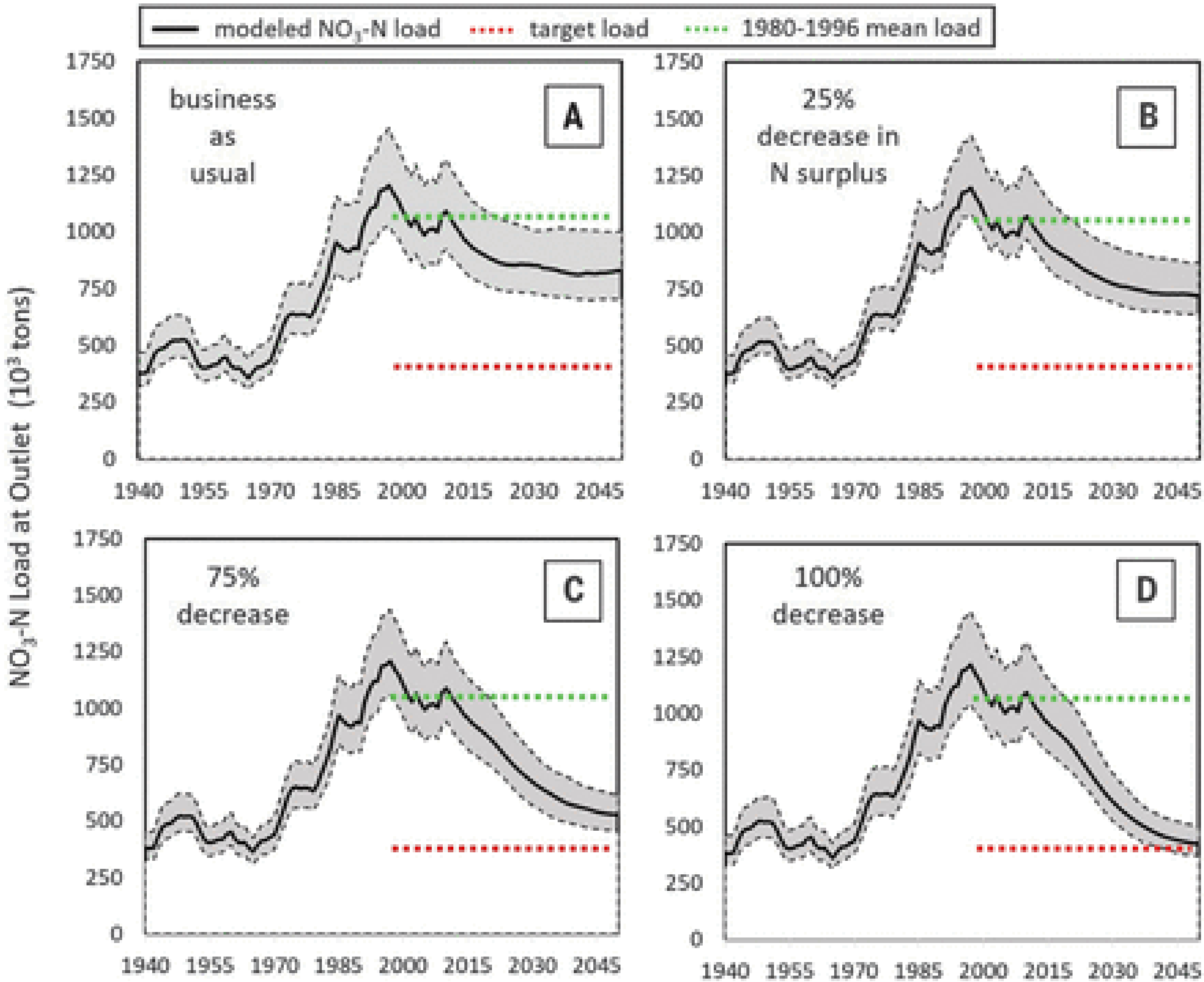

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Fig. 2 Model-predicted NO_3-N export from the MRB under future scenarios.

Scenarios include (**A**) business as usual (BAU) and then (**B**) 25%, (**C**) 75%, and (**D**) 100% decreases in the agricultural N surplus. The green dotted lines represent mean N loading for the period 1980–1996, and the red dotted lines represent target N loading to achieve water quality goals for the Gulf of Mexico. For these scenarios, reductions in N loading ranging from 11 to 55% will be achieved. Note that under all scenarios, it takes ~30 years to reach new steady-state loading levels after the 2017 shift in watershed management.

In addition, the time necessary to achieve a stated goal can vary depending on the magnitude of reductions in the N surplus. As an example, the WNTF set an interim goal to reduce N loading from the MRB by 20% by the year 2025. According to our model calculations, only an immediate reduction in the agricultural N surplus of 80% or more would allow us to reach this policy goal within the specified time frame (**Fig. 3A**). However, if policy goals were modified to allow more time to achieve the 20% improvement, more modest reductions in the N surplus could be implemented. The trade-offs between the speed at which improvements in water quality can be achieved and the extent to which watershed management must be modified are illustrated in **Fig. 3B**, which depicts the time-cost trade-off in a Pareto front framework (*23*). As indicated in the figure, the proposed 20% reduction in N loading could theoretically be achieved in 7 years with a 100% reduction in the N surplus (red arrows). Alternatively, it would take ~35 years to achieve the 20% reduction in N loading with an ~16% reduction in the N surplus (gray arrows).

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Fig. 3 Combined effects of watershed N surplus reductions and time on achieving N loading goals for the MRB.

(**A**) Predicted reductions in N loading by 2025 as a function of the reduction in the agricultural N surplus imposed in 2017 (note: 2025 is the interim WNTF target year for achieving a 20% reduction in N loading). (**B**) Cost-time trade-offs in achieving reductions in MRB N loads. The contour lines represent fractional reductions in N loading as a function of both percent reductions in the agricultural N surplus and the time required to see changes in loading. The red and gray arrows, respectively, demonstrate that it may take between 7 and 35 years to achieve a 20% reduction in N loading, depending upon the extent to which N surplus values are decreased.

With the ELEMeNT model it is possible to simulate the residence times of N within watershed soil profiles and along groundwater flowpaths and, hence, to calculate N age distributions at the mouth of the Mississippi River (see supplementary materials). Here, we define “age” as the time it takes for an N atom to travel from the landscape surface to the catchment outlet, including both time spent within the soil organic matter (biogeochemical lag) and time spent traveling along potentially slow groundwater transport pathways (hydrologic lag). The results suggest that, at present, more than 50% of NO_3-N exported from the watershed is >30 years of age, whereas only 25% is <5 years old (**Fig. 4**). As expected, the N age distributions also vary with time. For example, under the BAU scenario represented in **Fig. 4**, the proportion of NO_3-N greater than 30 years of age decreases from ~47 to 21% between 2010 and 2050. At the same time, the relative importance of younger N increases during this period, with the youngest N (0 to 5 years) increasing from 25 to 36% of loading.

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Fig. 4 Changing age distribution of MRB nitrate loadings to the Gulf of Mexico from 1940 to 2050 for the BAU scenario.

Note that in 2010, close to 50% of the catchment NO_3-N load is made up of N that has resided within the watershed for more than 30 years. In contrast, by 2050, the magnitude of N in this age range has shrunk to only 21%. As demonstrated by the changing proportions of legacy N, decreases in N loading under the BAU scenario (dark brown line) are driven almost entirely by reductions in sources of legacy N over the simulation period.

The present findings suggest that past land use and agricultural management are primary drivers of current N loading from the Mississippi River to the northern Gulf of Mexico. From 1970 to 2010, cropped area within the MRB increased by ~20% (*24*, *25*). During this period, fertilizer application rates peaked and livestock production intensified (*3*, *26*), leading not only to short-term increases in riverine N loading but also to accumulations of excess N in soils and groundwater (*27*, *28*). As steps are taken to improve nutrient management and implement new best management practices, we are beginning to see a decrease in N surplus values across the MRB and, in some areas, modest reductions in riverine N loading (*5*, *29*, *30*). However, the effects of any changes made today are inevitably modulated by legacy N already present within the watershed (*29*).

Our results first indicate that it will take decades to achieve the desired improvements in Gulf of Mexico water quality, even without the inevitable delays in implementation of selected conservation measures. Policy-makers must therefore consider this time lag to set realistic goals for the MRB. Additionally, our results show that to meet current goals for improvement—specifically the nearly 60% decrease in N loading deemed necessary to reduce the size of the hypoxic zone—would require action on multiple fronts. This action would include reductions in N inputs (e.g., more-targeted use of N fertilizer) as well as a major shift in land-use practices—perhaps a widespread conversion to perennial biofuel crops. Furthermore, a much larger emphasis on restoration of riparian wetlands, which can enhance removal of both current-year and legacy N that has already left the fields, could speed reductions in loads and reduce time lags (*31*). Thus, although our analysis suggests that large reductions in N loading may be possible, these reductions will require not just minor changes in land management but a fundamental alteration of the agroecosystem.

Supplementary Materials

www.sciencemag.org/content/360/6387/427/suppl/DC1

Materials and Methods

Figs. S1 to S3

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