2019

Comment On Legacy Nitrogen May Prevent Achievement Of Water Quality Goals In The Gulf Of Mexico

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Cite as: T. C. Ballard *et al.*, *Science* 10.1126/science.aau8401 (2019).

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

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Van Meter *et al.* (Reports, 27 April 2018, p. 427) warn that achieving nitrogen reduction goals in the Gulf of Mexico will take decades as a result of legacy nitrogen effects. We discuss limitations of the modeling approach and demonstrate that legacy effects ranging from a few years to decades are equally consistent with observations. The presented time scales for system recovery are therefore highly uncertain.

Van Meter *et al.* (*1*) developed a model to estimate nitrate loading from the Mississippi River Basin (MRB) to the Gulf of Mexico that allows for lag times between nitrogen (N) inputs to the soil surface and export from the continent. These lag times, or "legacy effects," can significantly influence the response times to management changes in watersheds. Their model simulations suggest that more than half of present loading is attributable to N inputs from more than three decades ago (*1*, *2*). The authors therefore conclude that meeting nutrient reduction goals for the MRB by the target year 2035 is impossible (*1*). Here, we argue that a wide range of legacy effects is consistent with the available data, hence the presented conclusions about recovery time scales after N input reductions are highly uncertain.

Van Meter *et al.* assess the influence of multidecadal legacy effects with calibrated residence times of N in soil organic matter, with observed MRB loading, and with a (misinterpreted, as we argue below) chloropigments sediment record.

First, although we agree that much of the N input to the land surface cycles through soil organic matter over several years, the Van Meter *et al.* model assumes that all surplus N follows this pathway (*2*). This assumption ignores the potential for nearly immediate increases in inorganic N loss from soils in tile drainage waters following N fertilization, such as after large precipitation events, where much of the N loss would not pass through an organic phase (*3*–*5*).

Second, to explore whether large contributions from multidecadal legacy effects provide the only plausible interpretation of observed loading, we explore two-variable linear regressions of loading constrained by the same observed 1955–2014 annual loads used in Van Meter *et al.* The two-variable regressions are simple by design, and we do not argue that they represent the full suite of processes operating in the field. Rather, we posit that if a simple regression can capture key features of the available observations, then (i) this is likely indicative of dominant processes, and (ii) the information content of those observations as they relate to constraining more complex processes and models is limited, precluding their use in calibrating or validating such models. The two variables considered are current-year or multiyear cumulative N inputs to represent legacy effects and current-year or multiyear cumulative basin-wide precipitation, which has been shown to influence MRB loading on interannual to decadal time scales (*6*–*8*). We use the same crop N surplus term from Van Meter *et al.* scaled by the annual fraction of the MRB covered in cropland to represent annual N inputs and freely available PRISM precipitation data (*9*).

We find that a wide range of legacy effect time scales (4 to 28 years) capture a comparable or greater amount of the variability in observed loading relative to the Van Meter *et al.* model (Fig. 1A), demonstrating that the loading data information content is insufficient to support a dominant role of multidecadal legacy effects. The regression models also illustrate the strong influence of recent (1- to 3-year cumulative) precipitation on observed loading interannual variability (Fig. 1), a factor not considered by Van Meter *et al.*

Third, Van Meter *et al.* evaluate their model by comparing modeled trends with chloropigments sediment data misinterpreted to be indicative of MRB loading. The chloropigments (Fig. 2; figure 1, A and B, in Van Meter *et al.*) are carotenoids specific to certain phytoplankton and reflect neither chlorophyll biomass nor primary production of carbon (*10*). For example, although zeaxanthin may indicate cyanobacteria presence, cyanobacteria constitute a minor component of total chlorophyll biomass in the region (*11*). Moreover, the sediment core selected (core D50) is located outside the region where hypoxia typically develops, limiting its applicability (*10*). A more appropriate indicator, biogenic silica, recorded in an area where hypoxia has been observed during 50 to 75% of surveys since 1985 (core E30) (*10*, *12*), does not support a dominant role of multidecadal legacy effects (Fig. 2).

Validation of legacy effects in the context of N reduction scenarios is especially difficult for the MRB because net N inputs primarily increase or remain stable over the observational data record. Published estimates of net anthropogenic nitrogen inputs for the MRB for years coinciding with the agricultural census are 23.2, 24.6, 26.9, 27.3, 27.3, and 31.4 kg N ha^{-1} $year^{-1}$ for 1987, 1992, 1997, 2002, 2007, and 2012, respectively (*13*). A downward trend in N inputs coupled with a multidecade lagged response in N outputs would better inform actual legacy effects time scales, but this has not been observed. Similarly, because soil N has primarily accumulated across the MRB during the study period (*14*), the relevant time scales over which it is exported, and thus its ability to constrain legacy effects, are unclear. Indeed, studies across the MRB have reported evidence of legacy effects ranging from just a few years to multiple decades (*15*, *16*).

The Van Meter *et al.* conclusion that system recovery following N input reductions will take decades is a result of their model calibration attributing large portions of observed loading to multidecadal legacy N. We have shown here that loading observations are equally consistent with legacy effects ranging from just a few years to multiple decades and that the chloropigment validation approach is unfounded. The uncertainty in estimating legacy effects time scales means that recovery times are equally uncertain. Recovery may indeed take decades, as Van Meter *et al.* suggest, but the recovery may also be much faster. For instance, tile-drained cropland, a primary contributor to MRB loading, appears to respond within a few years to management changes (*4*, *16*, *17*). Moreover, strategies that target N leaching from soil will reduce the impact of both recent and long-term legacy N stored in soils (*18*).

Regardless of the time scales of recovery, however, we wholeheartedly agree with Van Meter *et al.* that achieving desired water quality improvements in the Gulf of Mexico will require a suite of actions to significantly reduce N surplus and export of N remaining in the system. Uncertainty about legacy effects should not be used as a reason for delaying action.

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ACKNOWLEDGMENTS

We thank M. B. David and E. Sinha for generous and helpful discussions, and K. J. Van Meter and N. B. Basu for providing data from Van Meter *et al*. (*1*, *2*). **Competing interests:** The authors declare no competing interests. **Data and materials availability:** We use precipitation data from the PRISM Climate Group (*9*) and the R 3.4.3 computing language for analysis. All code is archived in the following GitHub repository: https://github.com/tristanballard/legacyN_comment.

24 July 2018; accepted 19 June 2019
Published online 23 August 2019
10.1126/science.aau8401

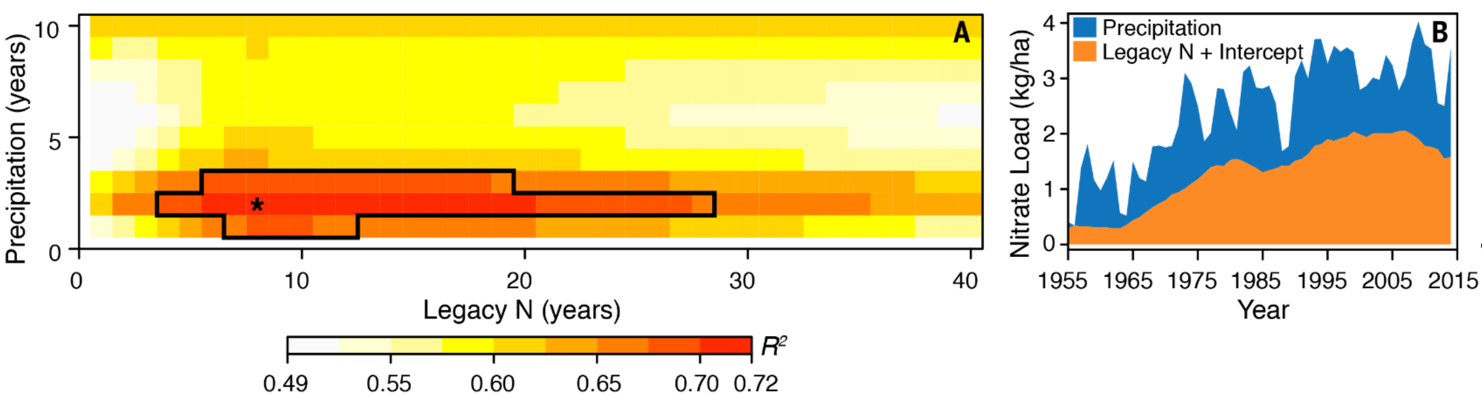

Fig. 1. Wide range of legacy effects explain observed nitrate loading. (**A**) We test the ability of a variety of legacy N effects to reproduce the same observed 1955–2014 nitrate loads used in Van Meter *et al*. using simple regression models based on legacy N and total annual basin-wide precipitation. Here we define legacy N as current-year to 40-year cumulative N inputs using the same crop N surplus term from Van Meter *et al*. The impact of precipitation is represented using cumulative precipitation over 1 to 10 years. Each variance explained (R^2) value indicates the fraction of loading variability explained by the corresponding two-variable regression. The black contour line indicates regressions with an R^2 exceeding that in Van Meter *et al*. ($R^2 = 0.67$), demonstrating that N legacy effects ranging from 4 to 28 years are at least as consistent with observations as the Van Meter *et al*. model. (**B**) Selecting the best-performing two-variable regression as an example [indicated by a star in (A)] suggests that legacy N—in this case, 8-year (i.e., sub-decadal) cumulative N inputs—explains longer-term trends in loading, whereas precipitation—in this case, 2-year cumulative basin-wide precipitation—explains shorter-term interannual variability.

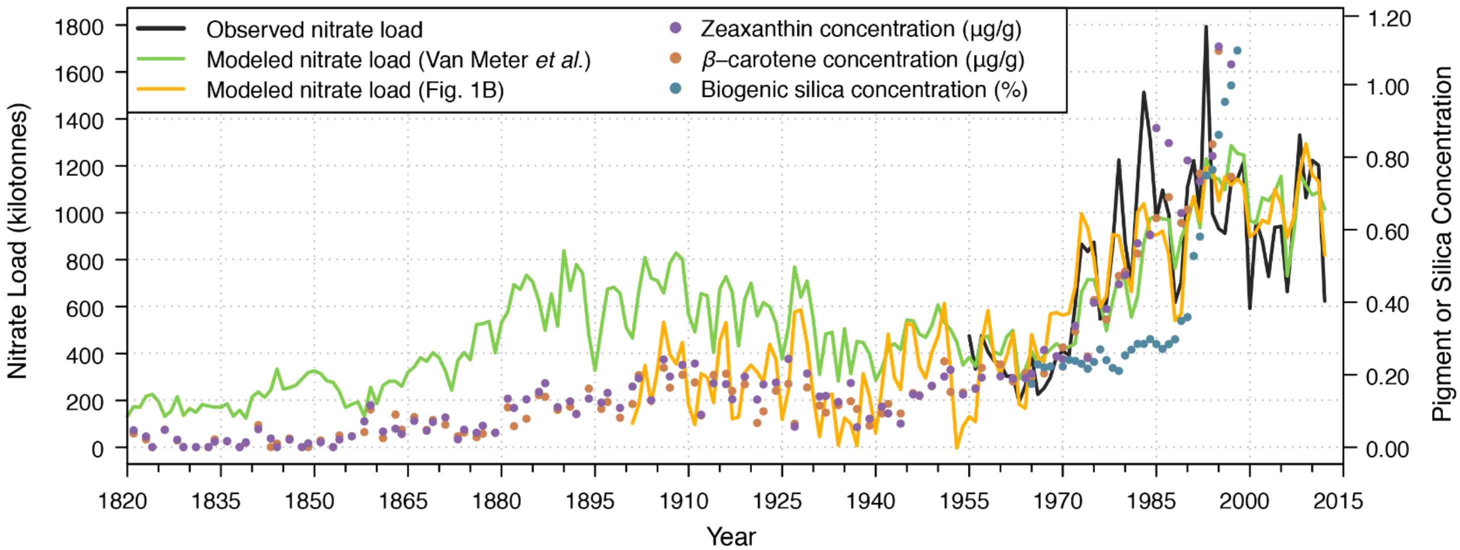

Fig. 2. Chloropigments data do not support the need to invoke multidecadal legacy effects. Modeled nitrate loads from Van Meter *et al*. (green, $R^2 = 0.67$) and from a two-variable regression based on 8-year cumulative N inputs and 2-year cumulative basin-wide precipitation (Fig. 1B, converted to units of kilotonnes) (yellow, $R^2 = 0.72$) both represent the observed loading (black) well. Note that modeled and observed loading are presented here on an annual basis, whereas it is unclear what multiyear smoothing was applied in Van Meter *et al*. The zeaxanthin (purple) and β-carotene (orange) chloropigments selected in Van Meter *et al*. do not consistently scale with the Van Meter *et al*. modeled loads, nor are they good indicators of productivity resulting from nitrate loading (*10*). Furthermore, the selected core (D50) is outside of the area of the Gulf of Mexico most sensitive to variations in loading. A more appropriate indicator, biogenic silica (*12*), from a more relevant location in the Gulf (core E30; cyan) does not provide evidence in support of multidecadal legacy effects. For visualization purposes, the range of the secondary vertical axis (Concentration) has been selected to maximize the correspondence between the zeaxanthin data and observed loads during the overlapping (1955–1997) period. The two-variable regression was hindcast to 1900, corresponding with the temporal extent of available precipitation data (*9*).

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Science, 365 (6455), eaau8401.