Science of the Total Environment 505 (2015) 149–153

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Cost of areal reduction of gulf hypoxia through agricultural practice

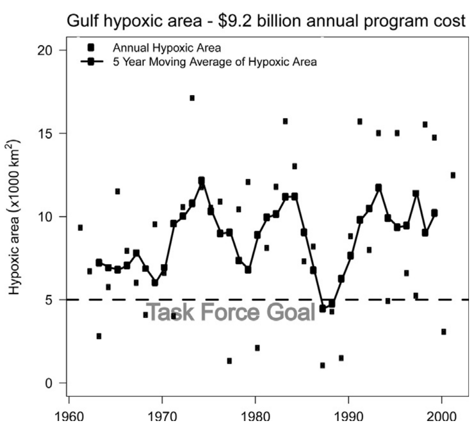
Gerald Whittaker [a,*], Bradley L. Barnhart [a], Raghavan Srinivasan [b], Jeffrey G. Arnold [c]

[a] *Agricultural Research Service, USDA, Corvallis, OR, United States*
[b] *Departments of Ecosystem Sciences and Management and Biological and Agricultural Engineering at Texas A&M University, United States*
[c] *Agricultural Research Service, USDA, Temple, TX, United States*

HIGHLIGHTS

- We calculate the cost to reduce Gulf hypoxia using agricultural conservation policy.
- Total annual policy cost is 9.2 billion USD not including agricultural price shocks.
- The Task Force hypoxia reduction goal is met in only twice in a 40 year simulation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form 26 September 2014
Accepted 29 September 2014
Available online xxxx

Editor: E. Capri

Keywords:
Hypoxia
Eutrophication
Gulf of Mexico
Nonpoint source pollution
Agricultural incentive policy

ABSTRACT

A major share of the area of hypoxic growth in the Northern Gulf of Mexico has been attributed to nutrient runoff from agricultural fields, but no estimate is available for the cost of reducing Gulf hypoxic area using agricultural conservation practices. We apply the Soil and Water Assessment Tool using observed daily weather to simulate the reduction in nitrogen loading in the Upper Mississippi River Basin (UMRB) that would result from enrolling all row crop acreage in the Conservation Reserve Program (CRP). Nitrogen loadings at the outlet of the UMRB are used to predict Gulf hypoxic area, and net cash farm rent is used as the price for participation in the CRP. Over the course of the 42 year simulation, direct CRP costs total more than $388 billion, and the Inter-Governmental Task Force goal of hypoxic area less than 5000 square kilometers is met in only two years.

Published by Elsevier B.V.

1. Introduction

Hypoxic growth in the Northern Gulf of Mexico causes large ecological damage and associated economic costs. Nutrients from agricultural practices in the Mississippi/Atchafalaya River Basin (MARB) are considered to be the major factor contributing to this hypoxic growth

* Corresponding author at: Agricultural Research Service, 3450 SW Campus Way, Corvallis, OR 97331, United States.
E-mail address: Jerry.Whittaker@ars.usda.gov (G. Whittaker).

http://dx.doi.org/10.1016/j.scitotenv.2014.09.101
0048-9697/Published by Elsevier B.V.

(Broussard et al., 2012; Raymond et al., 2012). In 1997 the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Task Force) was established for support of research and management activities dealing with eutrophication in the northern Gulf of Mexico. Task Force membership currently includes 5 federal agencies, 12 states and the tribes within the Mississippi/Atchafalaya River Basin. The Task Force has set a goal for Gulf hypoxic area of 5000 square kilometers for a 5-year moving average (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008). There have been studies of the cost of reducing agricultural nutrient loadings to the Mississippi River (Rabotyagov et al., 2010), and studies that calculate the amount of nutrient reduction required to meet the 5000 square kilometer goal (Forrest et al., 2011, 2012; Obenour et al., 2012; Scavia et al., 2013), but no calculation of the cost to approach the Task Force goal. We offer an estimate of the cost of an agricultural policy to reduce agricultural nutrient loadings in the Mississippi and the effect on the size of the Gulf hypoxic area that results.

2. Incentive policy for nutrient reduction

Among many agricultural conservation practices affecting stream nutrient loadings, the Conservation Reserve Program (CRP) provides a convenient policy for evaluation of hypoxia mitigation. The program is in effect a land-use change from agricultural to grassland, and is much simpler to model than alternative conservation practices such as buffer strips, contour farming, terraces, diversions, filter strips and others (Wang et al., 2011). The CRP is also the most effective in a physical sense, since it ends all agricultural operations including soil disturbance and application of agricultural chemicals. The price of application of the CRP conservation practice is also simpler to compute than alternative practices. Price calculation of other practices requires apportionment of labor, machinery and other inputs with the effect on yield. Under the CRP, the government pays a producer to take land out of production and plant a long-term, resource-conserving cover. The CRP establishes payment rates based on the average cash rent for comparable land (Food, Conservation, and Energy Act of 2008, Public Law 110—246, title II, section 2110, paragraph (b), dated June 18, 2008). The data on average cash rent of non-irrigated farm land used in CRP calculations is available at http://quickstats.nass.usda.gov/sector_desc=ECONOMICS&commodity_desc=RENT&agg_level_desc=COUNTY, accessed 9/1/2014.

The Upper Mississippi River Basin (UMRB) was selected for simulation of the effect of participation in the CRP on the size of the Gulf hypoxic area. Land use in the UMRB is approximately 40% agricultural, and the basin contains about 15% of the drainage area of the MARB. USGS estimates using the SPARROW (Spatially Referenced Regression On Watershed attributes) model (Smith et al., 1997) calculate that about 52% of the nitrate discharged to the Gulf is from the UMRB (Goolsby et al., 1997).

3. Use of CRP to meet task force goal

Given the magnitude of estimates of nutrient reduction required to meet the Task Force goal, about 60% by the most recent estimate (Obenour et al., 2013; Scavia et al., 2013), we hypothesized that a very large change to the current agricultural production configuration in the UMRB would be required to achieve a useful reduction in Gulf hypoxic area. The USDA Conservation Effects Assessment Project (CEAP) estimates that treatment of all under-treated acres in the UMRB would decrease nitrogen loadings by 33% from current agricultural practice (Conservation Effects Assessment Project (CEAP) Cropland Modeling Team, 2012), clearly insufficient to meet the Task Force goal. Therefore we simulated the change of all row crop land in the UMRB (54,185,298 acres in UMRB-SWAT) to grass under the Conservation Reserve Program. We note that the policy we simulate removes a large part of the US Corn Belt from production. We do not propose the enactment of such a change. The effects of such a large change would propagate through commodity prices and employment, and could even lead to internal migration. To model a politically feasible policy, for example, the acreage could be distributed among all watersheds in the Mississippi Basin. For the purposes of modeling and simulation of a perturbation of the nutrient delivery system to the Gulf of Mexico, the removal from production of all acreage in a single basin is simpler, and achieves the same result as an analysis of a distributed CRP acreage.

4. Methods

We used the Soil and Water Assessment Tool (SWAT) for simulation of the effect of an agricultural conservation policy on nutrient loadings in the Mississippi (Arnold and Fohrer, 2005). SWAT is a landscape level model for simulation of distributed hydrology, plant growth, nutrient use and fate, and agricultural practices, among many other processes. SWAT is widely used, and refereed journal citations of SWAT currently number 1451. SWAT divides the landscape into sub-watersheds connected by a stream network. Within each sub-watershed, all unique combinations of land cover, soil and soil type are modeled individually. While designed for use on large, ungauged basins, all of the processes that SWAT simulates can be calibrated to available data. Our selection of SWAT was based on the proven capabilities for simulation of hydrology, which compares favorably with specialized hydrological models (Smith et al., 2012), and for simulation of agricultural practices.

A special version of SWAT has been set up for the study of biofuel feedstock production in the UMRB. A detailed description of the inputs to SWAT-UMRB, including land use, management practices, soils, fertilizer application, and meteorological data, is available in Srinivasan et al. (2010). SWAT_UMRB was set up with 131 sub-watersheds, the 8 digit HUCs delineated by the USGS. SWAT-UMRB runs on a daily time step, and uses maximum and minimum temperatures and daily precipitation for basic weather inputs, where a separate weather data set was calculated from historical observations for each sub-basin for 1960–2001 using the gridded data approach of Di Luzio et al. (2008). National Hydrography Dataset was the source for stream configuration and the accompanying 90 m digital elevation model (DEM) provided slopes for watershed configuration and topographic parameter estimation using the SWAT ArcView interface. The soil data used was from the STATSGO base from the NRCS, USDA (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053629). Land use was obtained from the Cropland Data Layer (CDL) (http://nassgeodata.gmu.edu/CropScape/) and 2001 National Land Cover Data Base (NLCD2001, http://www.mrlc.gov/index.php).

SWAT-UMRB has been validated and applied in several studies (Secchi et al., 2011). The simulation of nitrogen loadings is the basis of this study, and a comparison of the simulated sum of nitrates and nitrites compared with observed values at Grafton, IL is shown in Fig. 1. The mean error is 7%. The distribution of errors is approximately normal, with a mean of 15.4 thousand metric tons and a standard deviation of 104.0. The two largest errors are an under-prediction of −232 thousand metric tons in 1987, where the simulation lags a year behind a large multi-year decrease in nitrogen loading, and an over-prediction of 226 thousand metric tons in 1993.

There has been no published linkage from SWAT-UMRB simulation outputs to the size of Gulf hypoxic area. Current biological models of Gulf hypoxic area use spring nitrogen loadings measured close to the mouth of the Mississippi River as a primary determinant (Scavia et al., 2013). There have also been several studies that use linear regression on weather based inputs and spring nitrogen loading at the mouth of the Mississippi River to predict Gulf hypoxic area (Turner et al., 2012; Mattern et al., 2013). There is a high correlation between monthly nitrogen flux at the outlet of the UMRB at Grafton, IL, and monthly nitrogen flux at the outlet of the MARB, and a strong correlation among nitrogen flux at both locations and the estimated area of Gulf hypoxia (Goolsby, 2000). We hypothesized that a statistical model regressing the observed

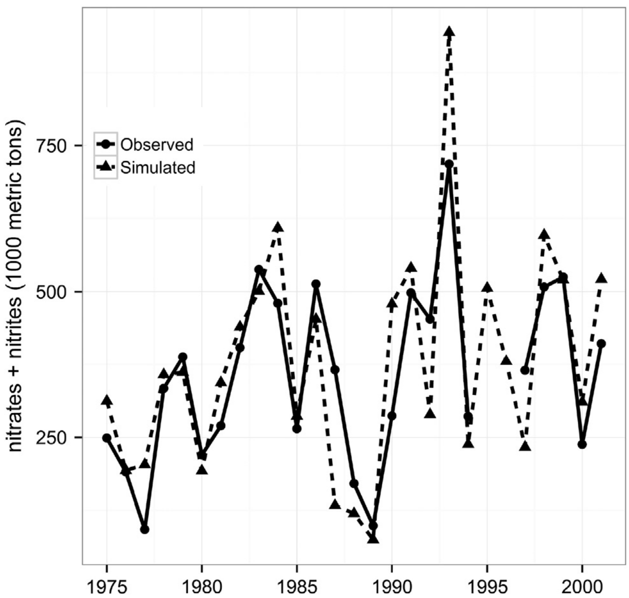


Fig. 1. Comparison of simulated and observed nitrogen loading at USGS Station ID 05587455 at Grafton, IL. There were no observations in 1995–96.

nitrogen loadings at the outlet of the UMRB on the area of Gulf hypoxia could be used to link simulated agricultural conservation practices in the UMRB with changes in area of Gulf hypoxia. We used nutrient flux for the UMRB for the independent variable in a regression model, available at http://toxics.usgs.gov/hypoxia/mississippi/flux_ests/five_basins/Upper-Miss-5-Large-2012.xls (accessed 12/4/2013), described in Aulenbach et al. (2007). The dependent variable in the regression is the estimated Gulf hypoxic area, and updates at http://www.gulfhypoxia.net. The nutrient response curve for nitrogen estimated with the biological model of Scavia et al. (2013) approaches a hypoxic area of zero for nitrogen flux of zero. Therefore we forced the regression to go through zero by not including an intercept in the regression estimate. The regression results are shown in Table 1 for the following regression:

$$hypoxic\,area = \beta_1 nitrogen\,flux + \beta_2 nitrogen\,flux^2 + random\,error$$

where the values of the coefficients β_1 and β_2 are shown in Table 1, along with the parameters of the error distribution. Both parameters are highly significant.

Summary statistics are residual standard error: 4382 on 24 degrees of freedom, multiple R-squared: 0.9143, adjusted R-squared: 0.9072, F-statistic: 128.1 on 2 and 24 DF, p-value: 1.565e − 13. We used the Akaike information criterion (AIC) to compare this regression model with the biological model from (10). The AIC penalizes models with more parameters, which explains the result of −7.74 for the Grafton model and 22.29 for the biological model, where the smaller number indicates the better fit. We conclude from an application of the Wilcoxon rank sum test in the R stats package (R Development Core Team, 2013)

Table 1
Regression model of the relation between nitrogen loading (flux) at the mouth of the UMRB and hypoxia area in the Gulf of Mexico. This model was used to predict the change in hypoxic area given a change in land use in the UMRB.
Second degree polynomial regression of nitrogen flux at Grafton, IL on Gulf Hypoxic area.

	β	$\beta_{s.e.}$	t value	Pr(>|t|)
Nitrogen flux	3.528e − 01**	5.654e − 02	6.239	1.9e − 6***
Nitrogen flux^2	−1.799e − 06	6.984e − 07	−2.576	0.0166*

*** $p < 0$
** $p < 0.01$
* $p < 0.05$.

(W = 334, p-value = 0.6189) that the residuals are from identical populations at the 0.05 significance level. To visualize the similarity of the two error distributions, we estimated the probability density function of each using a nonparametric technique (kernel density estimation) that makes no assumptions about the form of a probability distribution (see Fig. 2).

5. Results and discussion

The spatial setup for SWAT divides the watershed into subbasins connected by a stream network. Within each subbasin, unique combinations of landcover, slope, and soil type are defined as hydrologic response units (HRUs). To simulate participation in the CRP, we changed the landuse for each HRU with a row crop landcover to a grass cover. The result was a change in land use to grass for 219,281 square kilometers. From the SWAT output, we calculated nitrogen loadings from each subbasin by monthly aggregation of the daily loading of nitrates and nitrates as N, where load is equivalent to stream mass flux (Aulenbach et al., 2007). After running SWAT for 42 years, we used the simulated May nitrogen flux from the UMRB outlet at Grafton, IL in the regression model (Table 1) to predict Gulf hypoxia area. The nitrogen fluxes for the two simulations are compared in Fig. 3. The large variation in the effect of conversion to CRP is the most important feature, and is counterintuitive in that where the conservation practice (CRP) has the largest effect, the nutrient flux to the Gulf is also highest. This variation is due to the nature of agricultural pollution, which is an event driven phenomenon, where the driving events are rainfall and snowmelt. A May monthly flux where rainfall was low results in a smaller flux reduction while producing a smaller area of Gulf hypoxia. A high rainfall month shows a large reduction in flux due to the CRP, but Gulf hypoxic area remains large because of the increase in surface runoff. This is evidence that weather should be taken into account when setting a standard for Gulf hypoxic area size. If the 5 year moving average used as the standard were conditioned on rainfall or some comparable weather metric, the standard would reflect the underlying physical processes and results of conservation practices in a more meaningful way. (See Fig. 4.)

The high variability of nitrogen flux has important implications for the effects of conservation measures as global climate change continues. Wu et al. (2012) studied the UMRB under four General Circulation Models (GCMs) with different greenhouse gas emission scenarios.

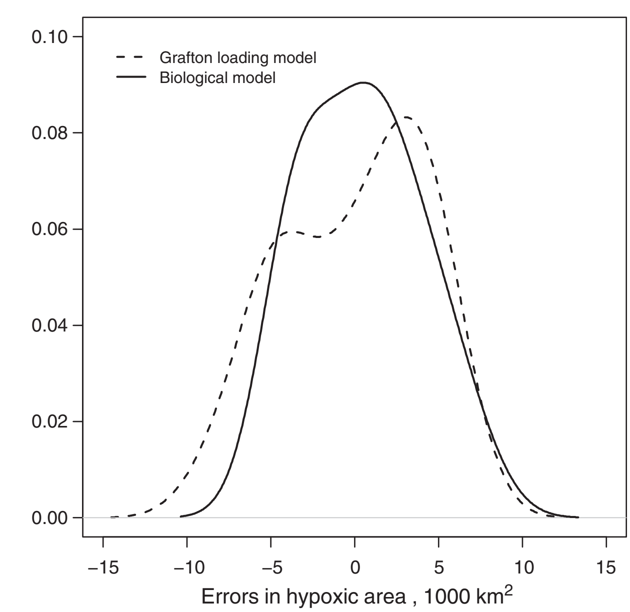


Fig. 2. Comparison of kernel density estimates of probability density functions of the residuals from the statistical model linking nitrogen loadings at Grafton, IL to Gulf hypoxic area and the residuals from the most recent biological model (Scavia et al., 2013).

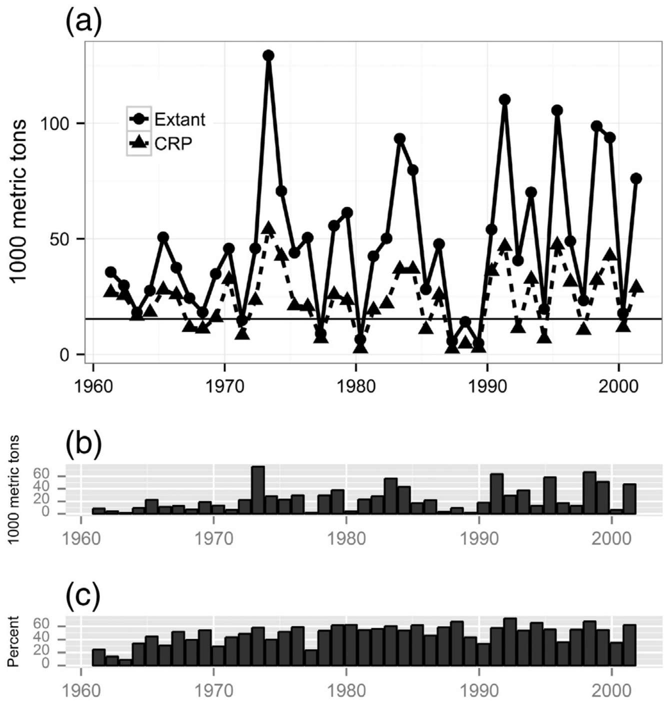


Fig. 3. Comparison of nitrogen flux (a) from existing agricultural landuse with conversion to CRP scenario, (b) reduction in nitrogen due to CRP and (c) reduction in nitrogen as a percent change from current landuse. The horizontal black line in (a) is the nitrogen flux that results in a 5000 sq.km. hypoxic area.

They found that water yield and variability in the UMRB would increase in the spring, at the time when the nutrient pulse that nourishes Gulf hypoxia occurs. Given the results in Fig. 3, we expect that the Task Force goal would be met in even fewer years where there was an increase in atmospheric carbon dioxide and climate change.

Although the CRP average price at the county level is available, where a large amount of land goes into the CRP, the average cash rent price will be a better estimate of actual cost because of better quality land entering the program and increased demand (Wu and Lin, 2010; Wu et al., 2013). We aggregated cash rent for non-irrigated land from county level to 8-digit HUC using a GIS and standard areal proration. Using the 8-digit HUC cash rent for non-irrigated land means as prices,

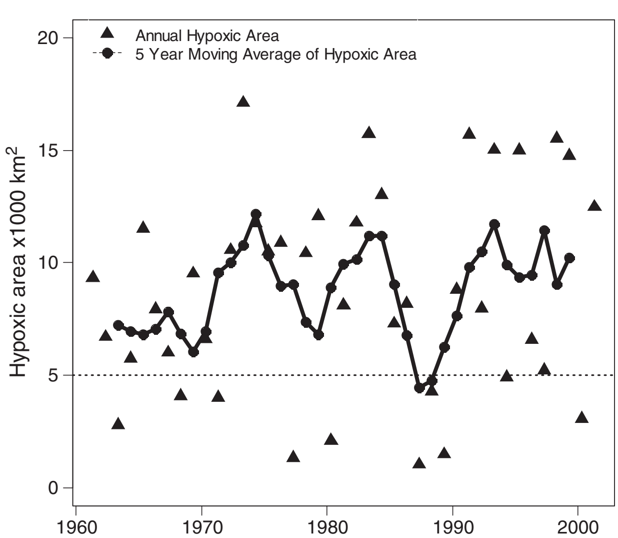


Fig. 4. Simulated Gulf hypoxic area with all UMRB row crop area in the Conservation Reserve Program. The Task Force goal calls for a hypoxic area limit of 5000 square kilometers where the area is calculated as 5 year moving average (solid line).

and the CRP area in each HUC, we calculated that the annual cost for 54.19 million acres of CRP would be $9.247 billion. Over the course of the 42 year simulation direct CRP costs total more than $388 billion and the Task Force goal is met in only two years (Fig. 4).

We assume that the UMRB has an agricultural production structure that is representative of the whole MARB, i.e., it would not be possible to find an area outside the UMRB where large reductions in nitrogen loading could be realized at lower cost than the CRP in the UMRB. That assumption is supported by a spatial regression where Sparrow estimates of nitrogen loadings and average crop sales at the 8-digit HUC level explain 76% of the variation of cash rent for non-irrigated farmland. Nitrogen loading is spatially correlated with land value and production, and it is unlikely that a “bargain” conservation practice will be available in another large contributing watershed in the MARB (Fig. 4).

6. Conclusion

The effect of removing millions of acres of the most productive farm land in the world from production will have indirect costs that dwarf the cost of the CRP rental. For every 1 million acres of corn production removed, corn price increases in the first period by $0.04 per bushel (Hausman et al., 2012). Corn, soybeans and wheat are highly correlated and can all be expected to rise. Other commodities using small grains as inputs, such as meat, will also increase. The CEAP cropland study for the UMRB (Conservation Effects Assessment Project (CEAP) Cropland Modeling Team, 2012) reports that in 2007 corn was produced on 32 million acres. Assuming a linear response, the effect of a shock of this magnitude would be expected to result in an increase of $2.88 per bushel, where the monthly U.S. corn price has ranged between $4.49 and $7.13 per bushel in 2013 (available on-line, http://www.usda.gov/nass/PUBS/TODAYRPT/agpr1013.pdf, accessed 12-11-2013). It is highly unlikely that the response to a supply shock of this magnitude would be linear. We expect that commodity price increases would be much higher, and the effects more far reaching throughout the economy.

The supply of agricultural land is highly inelastic, and the withdrawal of this amount of land from production would drive agricultural land values higher (Wu and Lin, 2010). Higher agricultural land values would of course require higher CRP payments (Wu et al., 2013), so that our estimate of the direct costs of CRP rental for the UMRB would be low. An analysis of these and other effects of such a massive shock to the agricultural system are beyond the scope of this paper. It is clear, however, that our estimate of $9.247 billion per year for a low probability of meeting the Task Force hypoxic goal is at the lower tail of the distribution of direct cost estimates. The results of this study show that it will be very costly to achieve the Task Force goal of a limited area of Gulf hypoxia, and may be beyond the capability of agriculture as it is currently organized.

Conflict of interest

The authors declare that they have no actual or potential conflict of interest.

References

Arnold JG, Fohrer N. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol Process 2005;19:563–72.
Aulenbach BT, Buxton HT, Battaglin WA, Coupe RH. Streamflow and nutrient fluxes of the Mississippi–Atchafalaya River Basin and subbasins for the period of record through 2005. Open-File Report 2007-1080. Washington, DC: U.S. Geological Survey; 2007.
Broussard WP, Turner RE, Westra JV. Do federal farm policies influence surface water quality? Agric Ecosyst Environ 2012;158:103–9.
Conservation Effects Assessment Project (CEAP) Cropland Modeling Team. Assessment of the effects of conservation practices on cultivated cropland in the Upper Mississippi River Basin. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2012.

Di Luzio M, Johnson GL, Daly C, Eischeid JK, Arnold JG. Constructing retrospective gridded daily precipitation and temperature datasets for the conterminous United States. J Appl Meteorol Climatol 2008;47:475–97.
Forrest DR, Hetland RD, Dimarco SF. Multivariable statistical regression models of the areal extent of hypoxia over the Texas–Louisiana continental shelf. Environ Res Lett 2011;6.
Forrest DR, Hetland RD, DiMarco SF. Corrigendum: multivariable statistical regression models of the areal extent of hypoxia over the Texas–Louisiana continental shelf. Environ Res Lett 2012;7:019501.
Goolsby DA. Mississippi Basin nitrogen flux believed to cause Gulf hypoxia. EOS Trans Am Geophys Union 2000;81(29):321–7.
Goolsby DA, Battaglin WA, Hooper RP. Sources and transport of nitrogen in the Mississippi River Basin; 1997.
Hausman C, Auffhammer M, Berck P. Farm acreage shocks and crop prices: an SVAR approach to understanding the impacts of biofuels. Environ Resour Econ 2012;53:117–36.
Mattern JP, Fennel K, Dowd M. Sensitivity and uncertainty analysis of model hypoxia estimates for the Texas–Louisiana shelf. J Geophys Res Oceans 2013;118:1316–32.
Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. Gulf Hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin; 2008 [Washington, DC].
Obenour DR, Michalak AM, Zhou Y, Scavia D. Quantifying the impacts of stratification and nutrient loading on hypoxia in the Northern Gulf of Mexico. Environ Sci Technol 2012;46:5489–96.
Obenour DR, Scavia D, Rabalais NN, Turner RE, Michalak AM. Retrospective analysis of midsummer hypoxic area and volume in the northern gulf of Mexico, 1985–2011. Environ Sci Technol 2013;47(17):9808–15.
R Development Core Team. R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2013 [ISBN 3-900051-07-0, URL http://www.R-project.org].
Rabotyagov S, Campbell T, Jha M, Gassman PW, Arnold J, Kurkalova L, et al. Least-cost control of agricultural nutrient contributions to the Gulf of Mexico hypoxic zone. Ecol Appl 2010;20:1542–55.
Raymond PA, David MB, Saiers JE. The impact of fertilization and hydrology on nitrate fluxes from Mississippi watersheds. Curr Opin Environ Sustain 2012;4:212–8.
Scavia D, Evans MA, Obenour DR. A scenario and forecast model for gulf of Mexico hypoxic area and volume. Environ Sci Technol 2013;47:10423–8.
Secchi S, Gassman PW, Jha M, Kurkalova L, Kling CL. Potential water quality changes due to corn expansion in the Upper Mississippi River Basin. Ecol Appl 2011;21:1068–84.
Smith R, Schwarz G, Alexander R. Regional interpretation of water-quality monitoring data. Water Resour Res 1997;33:2781–98.
Smith MB, Koren V, Zhang Z, Zhang Y, Reed SM, Cui Z, et al. Results of the DMIP 2 Oklahoma experiments. J Hydrol 2012;418–419:17–48.
Srinivasan R, Zhang X, Arnold J. SWAT ungauged: hydrological budget and crop yield predictions in the upper Mississippi River basin. Trans ASABE 2010;53:1533–46.
Turner RE, Rabalais NN, Justic D. Predicting summer hypoxia in the northern Gulf of Mexico: redux. Mar Pollut Bull 2012;64:319–24.
Wang X, Kannan N, Santhi C, Potter SR, Williams JR, Arnold JG. Integrating APEX output for cultivated cropland with SWAT simulation for regional modeling. Trans Am Soc Agric Biol Eng 2011;54(4):1281–98.
Wu J, Lin H. The effect of the conservation reserve program on land values. Land Econ 2010;86:1–21.
Wu Y, Liu S, Abdul-Aziz OI. Hydrological effects of the increased CO_2 and climate change in the Upper Mississippi River Basin using a modified SWAT. Clim Change 2012;110:977–1003.
Wu F, Guan Z, Yu F, Myers RJ. The spillover effects of biofuel policy on participation in the conservation reserve program. J Econ Dyn Control 2013;37:1755–70.