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Prioritizing conservation for the reduction of Gulf hypoxia using an environmental performance index

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ABSTRACT

The annual growth of hypoxia in the Gulf of Mexico is largely attributed to agricultural nutrient loadings that originate from the Mississippi/Atchafalaya River Basin (MARB). To effectively target conservation efforts throughout the entire MARB in order to reduce Gulf hypoxia, strategies to rank areas according to their impact on both agricultural production and ecosystem services are extremely important. In this paper, we utilize an Environmental Performance Index (EPI) to rank regions within the MARB according to their environmental performance, that is, their ability to produce agricultural outputs while minimizing nutrient loadings to the Gulf of Mexico. We compare our index rankings to previously used rankings of delivered yields alone and find the spatial distribution of rankings changes considerably when accounting for agricultural productivity. For example, the Corn Belt regions of central Iowa and northern Illinois no longer make up the lowest performing regions of the MARB after accounting for their high levels of agricultural production. Instead, regions along the Missouri river including central Missouri, western Iowa, and southeastern South Dakota as well as areas near the Ohio river including southern Illinois, western Kentucky, and southern Ohio now count among the lowest performing regions using the EPI ranking scheme. We suggest that incorporation of economic production value into large-scale prioritization of agricultural conservation within the MARB is essential to effectively reduce Gulf hypoxia while maintaining food security from efficient farm production.

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1. Introduction

The Mississippi/Atchafalaya River Basin (MARB) holds some of the most agriculturally productive land in the world. However, agricultural production is attained at the expense of soil and water quality due to intensive land use. One of the major ecosystem responses to agricultural production in the MARB is the annual summer growth of the hypoxic (oxygen ≤ 2 mg/L) region in the northern Gulf of Mexico. To address issues relating to hypoxia in the Gulf of Mexico and to reduce its growth, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Task Force) was formed in 1997 and is currently comprised of six federal agencies, 12 states, 2 regional groups, and a national tribal organization (Task Force, 2013). Within its recent 2013 Reassessment, the Task Force has reiterated its goal to reduce the 5-year average of Gulf hypoxia area to less than 5000 km^2 (Task Force, 2013). Estimates for the required reduction in nutrient loadings to meet the Task Force goal vary from 30% reductions in both N and P loadings (Rabotyagov et al., 2014) to as high as 65% reductions of N loadings alone (Scavia et al., 2013; Turner et al., 2012). Other studies suggest that loading reductions between 35% and 45% would meet the goal (Dale et al., 2007; Scavia et al., 2003). While these estimates vary drastically, it is widely acknowledged that meeting the Task Force goal will require widespread and appreciable nutrient reductions from the MARB.

Nutrient runoff from agricultural fields is the largest contributor to delivered N and P loadings from the MARB to the northern Gulf of Mexico. The highly cited SPAtially Referenced Regressions On Watershed attributes (SPARROW) estimates that the 2002 N and P loadings delivered to the Gulf from agricultural sources represent 63% and 43% of the total delivered loadings from the MARB (Alexander et al., 2007; Robertson et al., 2009). The remaining contributions are attributed to atmospheric deposition, urban sources, and wastewater treatment plants. To reduce the annual hypoxic growth in the northern Gulf, numerous studies model the spatial distribution of nutrient loadings delivered to the mouth of the Gulf

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of Mexico from the MARB (Robertson and Saad, 2013; White et al., 2014), and some suggest targeting conservation initiatives toward regions with the highest delivered yields (Robertson et al., 2009, 2014).

We extend this line of research by noting that efficient targeting of agricultural conservation for the reduction of Gulf hypoxia requires accounting for agricultural productivity in addition to environmental benefits of conservation implementation. We construct a ranking index for 8-digit HUC regions in the MARB that accounts for both agricultural production data and delivered nutrient yields the Gulf of Mexico. This index can then be useful to inform targeting strategies that seek to reduce the areal extent of hypoxia in the Gulf of Mexico without compromising food security from efficient farm production.

2. Overview of approach

Indices are widely used in the agri-environmental sciences in order to characterize the overall sustainability of a region in terms of environmental, economic, and social perspectives and to target and evaluate conservation policy. A comprehensive review is given in Hajkowicz et al. (2009). Also, we provide a few recent examples that demonstrate the diversity of studies available. Purvis et al. (2009) developed an aggregated farm-level index to design and evaluate EU policies related to agricultural and environmental sustainability. Also, Boyle et al. (2015) develop a nature value index that they suggest can be used to target farms with low biodiversity for sustainability and conservation practices, and Sabiha et al. (2016) construct a composite environmental impact index (CEII) to quantify the extent of environmental degradation due to agriculture in three districts of northwestern Bangladesh. Finally, in a study focused on targeting potential areas for future irrigation in Africa, Valipour (2015) estimated a number of indices using data from the Food and Agriculture Organization of the United Nations (FAO) and The World Bank Group (WBG).

Our index approach integrates economic and biophysical considerations by combining U.S. Census of Agriculture production data with the SPARROW model estimates for the MARB. Our Environmental Performance Index (EPI) follows the framework first introduced by Färe et al. (2004), who jointly consider greenhouse gas emissions and economic output for OECD countries in a static cross-country comparison. The EPI is defined as a ratio of Malmquist (1953) quantity indexes that measure relative performance in terms of desirable and undesirable outputs. The quantity indexes are constructed from Shephard (1970) distance functions that measure feasible increases in good outputs and decreases in bad outputs, relative to a common benchmark level of production. The resulting EPI reflects the relative ability of producers within the MARB to simultaneously expand production and reduce nutrient loading delivered to the Gulf.

Because the component quantity indexes for goods and bads are constructed from distance functions, the EPI satisfies a number of desirable properties from index number theory (Diewert, 1987, 1992) and can accommodate the multiple inputs and outputs of agricultural production as well as different forms of nutrient loading. For these reasons, Tyteca (1996) recommends the use of distance functions to measure environmental performance, while Färe et al. (2004) remark that they serve as 'perfect aggregator functions.' The EPI also relies solely on production quantity data and, importantly, does not require the use of *a priori* price information for nutrient loading levels. We estimate the production technology non-parametrically using Data Envelopment Analysis (DEA) (Charnes et al., 1978) methods that in some sense allow the data to reveal the production process without imposing a functional form. Instead, this estimation approach endogenizes the weights for aggregation as solutions to a linear programming problem that makes use of standard convexity assumptions to characterize the production technology.

Not surprisingly, given these aggregation properties, variations of this Malmquist-type EPI framework have been widely applied to measure environmental performance. Notably, Färe et al. (2006, 2010) extend the framework to a dynamic analysis of the U.S. power industry. Zhou and Ang (2008) adapt this framework to decompose the change in carbon dioxide emissions into measures of efficiency change for energy usage and emissions of OECD countries. Kortelainen (2008) incorporates ecological data for the EU member states to develop a dynamic eco-efficiency of production index. Ferraro (2004) illustrates the use of distance functions to prioritize watershed sites for conservation investment according to multiple land attributes. To our knowledge, this is the first study to apply the EPI framework to the general problem of nutrient loading from agricultural production, and its contribution to the area of Gulf hypoxia in particular. In addition, while numerous studies examine the use of indexes to target agricultural conservation expenditures (Claassen et al., 2008; Ribaudo et al., 2001), this is the first study to focus on the use of indexes for reducing the size of Gulf hypoxia area.

Several studies analyze the economic implications for implementing agricultural policy to reduce the size of Gulf hypoxia. For example, Doering et al. (1999) compare the cost-effectiveness of different management practices including N-loss reduction, fertilizer reduction, and wetlands restoration on reducing the size of hypoxia in the Gulf. They suggest a combination of 20% fertilizer reduction and wetland restoration to be the most cost-effective but note that direct evidence of environmental benefits from management practices is still limited (Doering et al., 1999). Ribaudo et al. (2005) suggest that credit trading between point and nonpoint sources may be an effective policy tool to reduce nutrients delivered to the mouth of the Gulf of Mexico. They also indicate that there are large spatial differences in the cost of N reduction between regions in the MARB. Rabotyagov et al. (2010) use an evolutionary algorithm to find the least-cost allocation of management practices and land retirement in the Upper Mississippi River Basin (UMRB) portion of the MARB to achieve nutrient reductions to the Gulf. They consider a variety of management practices, including fertilizer reduction, conservation tillage, the creation of grassed waterways, and the use of terraces, and they find that targeted nutrient strategies achieve the greatest reduction in nitrogen and phosphorus loadings at the mouth of the Gulf.

We contribute to this research by using the EPI to identify the spatial distribution of environmental performance over the entire MARB. This includes both the highly productive Corn Belt region of the UMRB as well as lower-producing subbasins reaching into the plains region, Ohio River Basin, and the Lower Mississippi. Our index combines U.S. Census of Agriculture production data with nitrogen and phosphorous loadings estimates from the USGS SPARROW model. We demonstrate that the EPI can be used to prioritize less efficient and lower-performing regions within the MARB for more effective implementation of agricultural policy and management practices to reduce the size of Gulf hypoxia.

The paper proceeds as follows. In the next section, we present the economic theory underlying environmental performance in more detail and outline the methods used to construct the EPI. Then, we describe the agricultural production and environmental data used in the study. Next, we discuss the calculated index values and show the spatial distribution of different ranking methodologies to rank areas within the MARB and prioritize lower-performing sites for agricultural conservation. Finally, we present conclusions and suggestions for future research.