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Analysis

Optimizing Spatial Land Management to Balance Water Quality and Economic Returns in a Lake Erie Watershed

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ABSTRACT

Significant reductions in phosphorous (P) inputs from cropland are needed to address the re-eutrophication of Lake Erie. Previous studies aimed at addressing non-point source pollution have primarily analyzed the effectiveness of conservation practices (CPs) as land-management strategies. However, the effectiveness and efficiency of these practices have not been compared to those of possible land-use changes. We develop a spatially explicit integrated modeling approach that compares the effectiveness and economic efficiency of alternative spatially optimal land-use and -management strategies for P abatement in the Sandusky River watershed. Using the Soil and Water Assessment Tool and data on costs and profits from crop and forest production and urban development, we evaluated joint impacts on P reduction and economic-returns for optimized land-use changes and/or implementation of CPs in the watershed. Results showed a combination of both CPs and land-use changes are likely required to meet current abatement targets for dissolved reactive phosphorus. Additionally, the combination of these approaches can generate a positive, synergistic effect on economic efficiency in meeting key policy targets. This is largely because the combined strategy will establish CPs on the most productive cropland, while achieving greater nutrient reduction through land-use change away from corn-soybean rotations on less productive lands.

1. Introduction

Nutrient loading resulting from extensive agricultural land development has been repeatedly linked with declines in surface water quality and related ecosystem and human health problems such as harmful algal blooms (Michalak et al., 2013; Schilling et al., 2010). To improve sustainability in land-use systems, including reducing such environmental impacts, recent studies have highlighted the importance of incorporating ecosystem services into decisions about land use and management (Goldstein et al., 2012; Guerry et al., 2015). At the same time, several regulatory programs for water quality have been put into place in the United States (e.g., Clean Water Act and Total Maximum Daily Loads (TMDL)) (Houck, 2002). However, current implementation of these efforts is far from sufficient to restore watersheds and reduce harmful algal blooms (Hoornbeek et al., 2013; NRC, 2009) largely because there are no mandatory regulations for controlling non-point source (NPS) pollution from agricultural land.

Among the multiple possible strategies to mitigate NPS pollution, many studies have focused on implementation of conservation practices (CPs) (Kalcic et al., 2016; Maringanti et al., 2009; Rabotyagov et al., 2014a; Scavia et al., 2014; Tomer and Locke, 2011; USDA NRCS, 2010). Agricultural CPs are management tools aimed at controlling soil erosion and reducing nitrogen (N) and phosphorus (P) discharge to surface waters (USDA NRCS, 2010). Previous studies have recommended spatial targeting of CPs as a cost-effective approach to reducing NPS pollution (Kalcic et al., 2015; Maringanti et al., 2011; Rabotyagov et al., 2014a), but the P abatement effectiveness of these approaches is limited (Bhattarai et al., 2009; Kleinman et al., 2011; Lemke et al., 2011). Also, various studies have highlighted the need to differentiate dissolved reactive phosphorous (DRP) from TP reductions because TP includes P adsorbed on mobilized sediments, whereas DRP includes only dissolved reactive P. In general, it is much more difficult for agricultural CPs to reduce soluble nutrient loadings, such as DRP, than to reduce sediments (Kleinman et al., 2011; Mueller-Warrant et al., 2012; Osmond et al., 2012). Several watershed level experiments led by USDA (Osmond et al., 2012) show that current agricultural CPs provide improvement of downstream water quality. In watersheds with substantial agricultural land, aggressive implementation of CPs at watershed scales would be

Abbreviations: USGS, United States Geological Survey; USDA NASS, United States Department of Agriculture National Agricultural Statistics Service; USDA ERS, United States Department of Agriculture Economic Research Service; USDA FSA, United States Department of Agriculture Farm Service Agency; USDA NRCS, United States Department of Agriculture Natural Resource Conservation Service

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needed to achieve even moderate (~30%) reductions in nutrient discharges (Bosch et al., 2013; Kalcic et al., 2016, 2015; Rabotyagov et al., 2014a; Volk et al., 2008).

Even if CPs were sufficient to meet NPS reduction targets, we need to consider whether they are the most economically efficient means of achieving those reduction targets. Before making large investments in new conservation actions, it is worthwhile to compare the physical effectiveness and economic efficiency of alternative strategies. In fact, some studies have suggested that diversifying agricultural landscapes with perennial plants should be a fundamental strategy for restoring agroecosystem health (Mueller-Warrant et al., 2012; Schulte et al., 2006). In recent year, "landscape approaches" have been recommended as a promising strategy to reconcile trade-offs in conservation practices (which help to abate P runoff) and agricultural production (which strongly governs economic gain from the land) (Sayer et al., 2013). By re-allocating land uses to suitable locations based on the comparative advantages of each land unit, previous studies have demonstrated that optimizing land-use patterns can be an effective approach to jointly improving regional economic and ecosystem services outcomes (Nelson et al., 2008; Polasky et al., 2008; Ruijs et al., 2015; Seppelt and Voinov, 2002). Although individual landowners may lose profit as a result of spatial optimization, the public-sector costs of providing incentives for land-use modification (e.g., converting corn-soybean rotations to other land-use types, like alfalfa hay, grasslands, or forests) might be lower, per unit of P abatement, than the costs to compensate farmers for implementing CPs.

To make watershed or landscape-scale land use and management choices more effective in lowering NPS pollution, it is essential to understand the comparative advantages of possible strategies in a spatially explicit manner (Ruijs et al., 2015). Various studies have utilized watershed modeling and spatial optimization algorithms to evaluate tradeoffs between agricultural production and environmental services under different policy scenarios (e.g., Lautenbach et al., 2013; Valcu-Lisman et al., 2016). Nonetheless, previous studies have rarely considered the role of changes in the spatial patterns of land use versus land management when assessing cost-effectiveness of CPs for reducing NPS pollution. Land retirement has been occasionally explored as land-use change and compared with CPs (Kling, 2011; Rabotyagov et al., 2014b), probably because it is relatively easy to implement and monitor. However, retiring cropland from production will be significantly more expensive relative to CPs on a field-by-field basis (Rabotyagov et al., 2014a), because government subsidies are often needed to compensate farmer's financial loss. A strategy that includes land-use changes and working land options, such as timber and hay production, could potentially be more cost-competitive than land retirement, depending on land conversion costs, management costs and prevailing economic markets for timber and hay. In this case, whether one strategy would be relatively more economically efficient than the other, given the same nutrient reduction objective, remains an open question. Therefore, an understanding of the tradeoffs and complementarities in physical efficacy and economic net returns and benefits of land-use (e.g. conversion to switchgrass or working forest) versus land-management (e.g. using CPs) approaches to reducing nutrient pollution is needed to fill a knowledge gap and to guide future planning. Previous studies have not compared these two approaches in an integrated modeling framework.

In this study, we aim to close the knowledge gap by developing an integrated modeling framework for Lake Erie's Sandusky River watershed that (i) evaluates the physical P abatement effectiveness of CPs, conversions of cropland to other land use/cover (LUC) types, and combinations of both strategies for reducing NPS pollution, and (ii) compares economically optimal spatial land-use and -management patterns based on different decision-making strategies. The joint ecological and economic performance of alternative land-use and CP options was estimated using an ecohydrological model combined with an economic net-returns component. Using this approach, we identify efficient spatial patterns of land-use and -management changes, given estimated field-level tradeoffs in performance on economic and nutrient-reduction goals. In our analysis, a solution is considered efficient if it maximizes economic returns to landowners for a given nutrient-loading reduction outcome, and vice versa. Instead of providing a single optimal solution, we developed a Pareto efficiency frontier that represents a range of nutrient-reduction objectives and their associated maximum economic returns for landowners.

2. Materials and Methods

2.1. Study Area and Scenario Development

Using data from the watershed of the Sandusky River in northern Ohio, we demonstrate the opportunities for an integrated approach to reducing non-point source pollution [see supplemental information (SI) Fig. S1a]. The watershed covers about 3458 km^2 and is dominated by cropland (> 80%) with some areas of urban development (Fig. S1b). Over 85% of the cropland is maintained as corn-soybean (C-S) rotation (USDA NASS, 2016). The landscape is generally flat, with some gently rolling plains in the central and southern portions (Fig. S1c). About 32% of the watershed's soil (Fig. S1d) is in the poorly or very poorly drained category (USDA NRCS, 2015) and artificial subsurface (tile) drainage is used to support agricultural production by lowering the water table below the crop rooting zone.

The Sandusky watershed is part of the Lake Erie basin, which has received increased public attention due to recurrent massive microcystis blooms. In 2011, Lake Erie experienced its largest recorded bloom (Michalak et al., 2013) and in 2014 a significant bloom rendered drinking water unsafe for the city of Toledo. To restore good water quality, the International Joint Commission (IJC) established the Lake Erie Ecosystem Priority in 2012, and recommended that the United States and Canadian governments take action to significantly reduce P loading to Lake Erie (IJC, 2014). To decrease the hypoxic area in the central Lake Erie Basin by 50% and limit the number of hypoxic days to 10 days per year, the IJC recommended 46% and 78% reductions in the total phosphorous (TP) and DRP loads, respectively, relative to the 2003 to 2011 and the 2005 to 2011 annual averages. Notice that these targets apply to combined TP and DRP loads from the western and central basins. In addition, some studies have suggested that control of DRP loads should be the focus in the study area, because it is more directly related to the algal bloom problem (IJC, 2014; Scavia et al., 2014).

By comparing the relative economic efficiency of three approaches to P reductions, with each scenario resulting in an efficiency frontier, our analysis will help policymakers understand the tradeoffs between land-use and -management approaches, and between agricultural production (e.g. crops, timber, and hay) and P reduction under each scenario. To establish a baseline, we assume farmers will maintain any cropland in the watershed as a C-S rotation. Spatial explicit data on current CP coverage is not publically available for the region (Kalcic et al., 2016). A recent survey for the western Lake Erie basin (USDA NRCS, 2011) shows that about 65% of the soybean acres planted are grown using no tillage, which is helpful for reducing soil erosion. However, only 19% of corn acres were planted using no-till. Using data from 2012 U.S. Agriculture Census (USDA NASS, 2012) and 2016 Crop Acreage Data (USDA FSA, 2017) reported to USDA FSA, it can be estimated that about 11.5% of the cropland in the watershed is currently under CPs (See *SI text: Exiting CP Coverage*). For the baseline simulation, we assume that no CPs on cropland, except no tillage for soybean. The three P reduction scenarios are:

(1) *Optimizing placement of CPs for each level of P abatement*: selected C-S fields receive one of five frequently adopted CPs (Tomer and Locke, 2011), including reduced tillage, no tillage, vegetative filter strips, grassed waterway, and winter cover crops. We added to this list a nutrient management option, assuming that farmers reduce