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Research article

Spatially explicit methodology for coordinated manure management in shared watersheds

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ABSTRACT

Increased clustering and consolidation of livestock production systems has been linked to adverse impacts on water quality. This study presents a methodology to optimize manure management within a hydrologic region to minimize agricultural phosphorus (P) loss associated with winter manure application. Spatial and non-spatial data representing livestock, crop, soil, terrain and hydrography were compiled to determine manure P production rates, crop P uptake, existing manure storage capabilities, and transportation distances. Field slope, hydrologic soil group (HSG), and proximity to waterbodies were used to classify crop fields according to their runoff risk for winter-applied manure. We use these data to construct a comprehensive optimization model that identifies optimal location, size, and transportation strategy to achieve environmental and economic goals. The environmental goal was the minimization of daily hauling of manure to environmentally sensitive crop fields, i.e., those classified as high P-loss fields, whereas the economic goal was the minimization of the transportation costs across the entire study area. A case study encompassing two contiguous 10-digit hydrologic unit subwatersheds (HUC-10) in South Central Wisconsin, USA was developed to demonstrate the proposed methodology. Additionally, scenarios representing different management decisions (storage facility maximum volume, and project capital) and production conditions (increased milk production and 20-year future projection) were analyzed to determine their impact on optimal decisions.

1. Introduction

Agriculture is a leading cause of surface water quality deterioration in streams, lakes and rivers worldwide (Malmqvist and Rundle, 2002). Impairment of more than 94,000 miles of streams in the U.S. was attributed to agricultural activities (United States Environmental Protection Agency, 2009). This impairment mainly occurs as a result of non-point source (NPS) pollution, i.e., the transport of nutrients, primarily nitrogen (N) and phosphorus (P), in addition to pathogens and sediments from agricultural soils to surface water through runoff, erosion, and leaching (Alexandridis et al., 2015). One of the key symptoms of aquatic systems nutrient enrichment is eutrophication, which manifests as increased water turbidity, toxic blooms of plankton and algae, and fish kills (Carpenter et al., 1998). Global loss of potable water, human health complications, loss of aquatic biodiversity, and the development of hypoxic (dead) zones in coastal marine ecosystems have also been attributed to eutrophication (Codd, 2000; Dodds et al., 2009; Hautier et al., 2009; Rabotyagov et al., 2014). The current shift towards expansion of arable lands and intensification in cropping, which is projected to grow in the coming decades, will further increase water quality deterioration (Tilman et al., 2002).

Targeting NPS pollution is a major challenge due to its spatial and temporal heterogeneity (Rissman and Carpenter, 2015). Various landscape measures, referred to as best management practices (BMP) have been adopted in an effort to minimize NPS pollution. Examples of BMP include filter strips, grass waterways, and terraces. Such measures reduce nutrient transport and the erosive impacts of storm water, reducing NPS pollution. In the context of crop-livestock systems, producers are encouraged to

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adopt agriculture-related BMPs, such as, nutrient management planning, manure storage, careful timing of manure and fertilizer application, regular soil and manure testing, and reduced tillage to reduce edge-of-field nutrient losses (Kleinman et al., 2012; Natural Resources Conservation Services, 2012). Operators of large livestock farms, concentrated animal feeding operations (CAFOs), are required to obtain pollutant discharge elimination permits (PDES) after the development of nutrient management plan which include manure storage capacity, available land base and crop rotations. Small and medium livestock production farms in many states are not yet required to submit nutrient management plans for review. On many of these farms, manure storages are often lacking due to cost barriers. Consequently, timing and rate of manure field applications are guided by disposal scheduling, not agronomic recommendations. In such cases, manure nutrients may be underutilized by growing crops leading to soil P buildup and consequently increased transport of P in runoff from fields to surface water (Sharpley, 2016; Sørensen and Jensen, 2013). Manure spreading during winter on frozen soils may lead to increased phosphorus runoff if soils had significant moisture during freezing or reach saturation during snowmelt, particularly if phosphorus is applied on top of snow cover (Lewis and Makarewicz, 2009; Srinivasan et al., 2006; Williams et al., 2010). Similarly, manure application close to rainfall events increase phosphorus runoff from agricultural fields (Vadas et al., 2011). Under these conditions, the establishment of individual or shared manure storages to serve small- and medium-sized farms can play a key role in reducing P runoff through facilitating manure applications at agronomically appropriate times and rates. Manure storages also allow the implementation of advanced manure processing technologies, i.e., liquid-solid separation and anaerobic digestion (Aguirre-Villegas et al., 2014; Liu et al., 2016) which improve the economics of transporting manure nutrients out of eutrophic watersheds.

The success of environmental interventions relies on spatial targeting of key contributing areas (Wardropper et al., 2015). Similarly, the cost of implementation and the allocation of the cost burden are major obstacles facing such interventions. In the case of new manure storages, decisions pertaining to capacity, number, and location of these storages are key to ensure the feasibility and efficacy of implementation. Formulating this problem as a mathematical optimization problem can help find an optimal solution that maximize environmental return on investment and reduce operational costs while allowing defined constraints such as project budget and maximum storage capacity.

Single and multi-objective optimization models have been used extensively in agricultural production to optimize livestock feed formulation (Castrodeza et al., 2005; Peña et al., 2009), irrigation scheduling (Pham et al., 2013; Raju and Kumar, 1999), and fertilization rate optimization (Zheng et al., 2013). Additionally, holistic optimization models have been developed to increase combined crop-livestock production efficiency, e.g., maximize nutrient use efficiency, minimize production cost, and maximize profitability, while also improving farm sustainability (Groot et al., 2012; Liang and Cabrera, 2015). Giasson et al. (2002) developed a farm management optimization model that targets the reduction of phosphorus index (PI) in fields, as well as the operational costs associated with manure hauling and application (Giasson et al., 2002). The optimization objectives, i.e., mean PI, standard deviation of PI, and operational costs were combined into a global objective function using weights that convey importance of weighted functions. Similarly, optimization models were developed to assist in selecting BMP options, i.e., grass waterways, filter strips, and diversions within watersheds and sub-watersheds to minimize P runoff (Kaini et al., 2012; Kao and Chen, 2003). Few studies, however, have targeted manure management among multiple producers in a larger geographical region, i.e., at watershed or sub-watershed levels. Catma and Collins (2011) developed a watershed-level optimization model to eliminate excess manure phosphorus in the Chesapeake Bay watershed (Catma and Collins, 2011). Their proposed model minimizes transportation and processing cost for livestock and poultry manure between counties using processing options such as incineration, pelletization, and composting to re-distribute manure, or alternatively, export it from the watershed. The spatial-aggregation used in that model (county-level) makes it unsuitable for targeting smaller watersheds or sub-watersheds. There is a need for system-level decision-support tools that assist producers and regulators in addressing livestock-related water quality problems through coordinated management. Such tools need to be data-rich in order to capture the complexity of the decision space and should produce provably optimal decisions. The goal of this study is to present a spatially-explicit optimization tool to help design and place optimally sized manure storage facilities to achieve water quality improvements. To demonstrate the optimization tool, we develop and present a case study of contiguous two sub-watersheds in the Yahara River watershed (Dane County, Wisconsin, USA).

2. Material and methods

The conceptual framework underlying the decision-support tool presented in this study is illustrated in Fig. 1. The tool is built around a mathematical optimization formulation (a mixed-integer optimization model) capable of making discrete decisions to guide the placement of storage facilities as well as decisions regarding manure transportation flows and quantities. The model relies on livestock and cropland data specific to the study area. Data needed for the case study development was collected from agricultural surveys, as well as from geospatial data (Table 1). A key component of this model is the geo-referenced dataset of livestock farms in the study area, which includes animal types and herd size. Geospatial analysis and mapping software, ESRI ArcGIS Desktop Release 10.4 (Redlands, CA: Environmental Systems Research) was used to derive the necessary data from various geospatial data layers. Computation models and data processing were carried out using MATLAB R2015a software (The Mathworks, Inc., Natick, MA, USA) while the mathematical optimization problem was formulated using AMPL version 3.1.0.201510231950 (AMPL Optimization, Inc., Albuquerque, NM, USA) and solved using CPLEX solver version 12.0 (IBM Corp., Armonk, NY, USA).

2.1. Model assumptions

Few assumptions, listed below, were made regarding manure management practices in the study area in order to facilitate modeling manure and storage practices:

I. The study area is sufficiently large and homogeneous and, consequently, no manure is hauled for land application across the study area boundary.
II. Crop fields and livestock operations are decoupled so as to allow manure application from any livestock operation to any crop field provided that applied manure does not exceed the maximum threshold for that field.
III. New storage facilities can be shared by more than one livestock (community storage).
IV. Field application of stored manure is carried out twice a year, 6 months apart, and all manure storages are completely emptied every 6 months.
V. All herds are assumed to be housed in confinement (no pasture based systems).