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A novel framework for analysis of cross-media environmental effects from agricultural conservation practices

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ABSTRACT

Agricultural ecosystems are a source of greenhouse gas (GHGs) emissions and losses of nutrients to waterways. Several studies have recognized this and have documented the potential to reduce GHG fluxes and nutrient loss to waterways by using carbon offsets to fund the implementation of land retirement and afforestation. However, the ability to use land for both agricultural production and environmental conservation is also important. This study develops a novel analytical framework that is used to examine the cross-media (water and air) environmental effects of implementing offset-funded conservation practices in a working-lands setting. The framework is applied to a case study which examines the extent to which carbon pricing can affect practice implementation costs and the optimal distribution of these practices throughout an agricultural watershed. Results indicate that carbon offsets can reduce conservation practice implementation costs and have the potential to reduce greater amounts of nonpoint source pollution for a given cost of implementation. This conclusion has significant implications for policymaking, particularly with regard to using markets for GHG emissions to achieve water quality improvements where water quality trading or government conservation programs have historically been unsuccessful.
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1. Introduction

Row crop agriculture plays a significant role in impacting environmental quality. Losses of the nutrients nitrogen (N) and phosphorus (P) from farm fields to surface waters degrades water quality and leads to conditions such as hypoxia in the Gulf of Mexico (Lohrenz et al., 1997; Goolsby et al., 2001; Rabalais et al., 2001; NOAA, 2010). Agricultural land management practices are also known to affect fluxes of greenhouse gases (GHGs) and carbon sequestration (West and Post, 2002) and can contribute to nitrous oxide acid (N_2O) fluxes, a potent GHG that has nearly 300 times the global warming potential (GWP) of CO_2 (Wagner-Riddle and Thurtell, 1998; Six et al., 2004; McSwiney and Robertson, 2005; Kim and Dale, 2008). These cross-media environmental impacts of agriculture have been well-described by the N cascade, which illustrates the behavior of reactive N in the environment (Galloway et al., 2003).

Several researchers have recognized that agriculture is a source of both GHG emissions and nonpoint source (NPS) water pollution and have proposed innovative policies aimed at improving the quality of affected environmental media, including air, land and water (Dwyer et al., 2009; Mehan III et al., 2009). These previous studies focus on the potential to use conservation practices such as land retirement and afforestation to improve water quality and wildlife habitat. Because they sequester carbon in soil and vegetation, these practices can be funded through carbon offsets. However, recent research into the effects of various agricultural land management practices has the potential to expand the portfolio of conservation practices available to include practices implemented on working lands such as cover cropping and fertilizer management (Wagner-Riddle and Thurtell, 1998; Six et al., 2004; McSwiney and Robertson, 2005; Kim and Dale, 2008). These practices have the potential to improve environmental quality by reducing both NPS water pollution and GHG fluxes while maintaining agricultural productivity.

A better understanding of the role that agriculture plays in influencing environmental outcomes involving land, air, and water resources enables the development of creative policies for improving environmental quality. This study develops a novel framework by combining GHG and hydrological modeling with an optimization algorithm to evaluate the optimal allocation of various agricultural conservation practices within a watershed. This framework can be used to analyze the cross-media environmental impacts from these practices and has the potential to inform the development of innovative policy measures to improve environmental quality. The following section develops this analytical framework. The third section applies the framework to a case study of the Wildcat Creek Watershed (WCW), an intensely farmed watershed in West-Central Indiana that is typical of the Corn Belt region of the United States.

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This case study investigates the potential for using carbon offsets to fund the implementation of working-land conservation practices and analyzes the cross-media environmental impacts from doing so. The fourth section concludes the study and provides a discussion of the potential for using the framework in policy formation.

2. Materials and methods

In order to fully evaluate the environmental impact of implementing agricultural conservation practices, a framework was developed to quantify the effects of practice implementation on both GHG fluxes and NPS pollution. The framework developed here uses an ensemble modeling approach, combining the outputs of GHG and hydrologic simulation models for use as inputs to an optimization model. This optimization model then evaluates alternative spatial allocations of conservation practices within a watershed by jointly minimizing the cost of practice implementation and pollution. The practices analyzed for this study include no-till farming (NT), fertilizer management (FM), the implementation of a cover crop (CC), and all four possible combinations of these three practices (NT + CC, FM + CC, FM + NT, NT + FM + CC). These practices were included in this study because each has been found to have some effect on the control of both NPS pollution (Angle et al., 1984; Mannering et al., 1985; Tilman et al., 2002) and GHG emissions (Wagner-Riddle and Thurtell, 1998; Six et al., 2004; McSwiney and Robertson, 2005; Kim and Dale, 2008). "NT" indicates continuous no-till for both corn and soybeans. "FM" means that total N applied to the crop, including starter N and the N contained in diammonium phosphate (18–46–0), was reduced from 208 kg ha^{-1} to 180 kg ha^{-1}. "CC" indicates the presence of an annual ryegrass (*Lolium multiflorum*) cover crop that was planted immediately after grain harvest and burned down with herbicide before planting the following spring.

2.1. Greenhouse gas simulation model

Modeling the GHG emissions reductions from various conservation practices requires the use of a model that can simulate the soil N and carbon dynamics that result from various land management practices at the field scale. A model that has been widely used for this application is the DAYCENT model (NREL, 2011), which can estimate the fluxes of soil organic carbon as well as the trace gases nitrous oxide (N_2O) and methane (CH_4) from land to the atmosphere (Del Grosso et al., 2005). DAYCENT has also been found to be more accurate in predicting N_2O fluxes than simple UN IPCC emissions coefficients (Delgado et al., 2010).

Using soil data from the USDA Web Soil Survey (USDA, 2009), DAYCENT was used to simulate the changes in GHG fluxes that result from the implementation of the seven conservation practices (NT, CC, FM, NT + CC, NT + FM, CC + FM, NT + CC + FM) for all of the dominant soils in a given watershed relative to a baseline scenario (see online Supplementary Data for DAYCENT modeling details). The baseline scenario consists of a corn-soybean rotation with conventional tillage. Once these fluxes were quantified, ArcGIS (ESRI, 2011) was used to calculate the area-weighted changes in average per-hectare GHG flux from each of the conservation practices.

2.2. Hydrological simulation model

Analysis of the effects of agricultural land management on a hydrological region requires a watershed-scale model capable of simulating the complex relationships between landscape characteristics and nutrient fluxes. The Soil and Water Assessment Tool (SWAT) is widely used, well-suited to researching the effects of land management strategies on a hydrological region, and is particularly

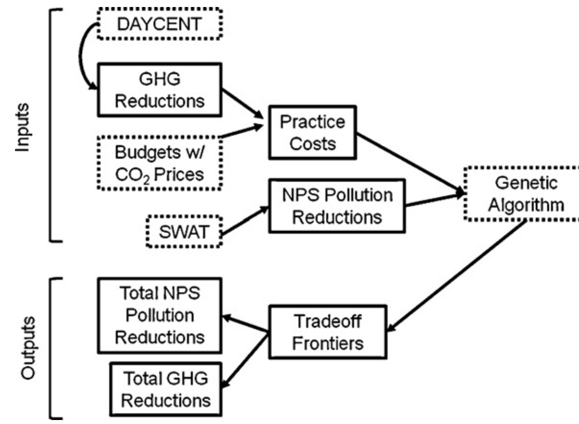

Fig. 1. Flow diagram of framework components.

appropriate for simulating nutrient fluxes from tile-drained agricultural watersheds (Arnold et al., 1998; Singh et al., 2005; Du et al., 2006). This study employed a SWAT model of the WCW developed by Cibin Raj and Indrajeet Chaubey of Purdue University's Agricultural and Biological Engineering Department (see Cibin et al., in press for details). The implementation of each of the seven conservation practices was modeled using SWAT. The average per-hectare changes in NPS pollution from each conservation practice – relative to the baseline scenario – were then calculated.

2.3. Optimization algorithm

Although SWAT is capable of modeling the effects of land management strategies in an agricultural watershed, using the model alone to determine the placement of conservation practices in a watershed that would jointly minimize both cost of practice implementation and pollutant load would be a tedious iterative exercise. Several researchers have recently used watershed models such as SWAT in conjunction with a search optimization technique known as a genetic algorithm (GA) that employs the concept of the biological processes of evolution in order to optimize some objective function (Srivastava et al., 2002; Jha et al., 2009; Maringanti et al., 2009; Rabotyagov et al., 2010). An advantage to GAs is their ability to search massive quantities of potential solutions in order to find the optimal one. Such a technique is useful for evaluating environmental and economic tradeoffs associated with conservation practice placement within an agricultural watershed as several practices can potentially be employed in each field, and over the course of an entire eight-digit watershed, the potential number of allocations is daunting; for example, a watershed with 400 farm fields and 7 potential conservation practices for each field can have 7^{400} potential practice allocations. Further, GAs are helpful in optimizing models that are composed of highly nonlinear and discontinuous functions because they select values for comparison over the entire universe of potential solutions, making them better-suited for solving complex models for global optima than nonlinear programming models.

Because the decision about whether to implement a conservation practice is based on both its cost and the effectiveness of pollution control, a variant of the GA that is particularly well-suited for use in optimizing conservation practice implementation in a watershed is a multiobjective genetic algorithm (MOGA). A MOGA can be used to find a set of optimal solutions known as the "Pareto frontier," which takes into account the tradeoffs between competing objective functions (Fonseca and Fleming, 1993). It should be noted here that the "Pareto frontier" that results from this model is distinct from an economic "Pareto frontier" in that the monetized benefits from reducing water pollution are not accounted

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