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Analysis

Cost-effective Land Use Planning: Optimizing Land Use and Land Management Patterns to Maximize Social Benefits

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ABSTRACT

Improving water quality and other ecosystem services in agriculturally dominated watersheds is an important policy objective in many regions of the world. A major challenge is overcoming the associated costs to agricultural producers. We integrate spatially-explicit models of ecosystem processes with agricultural commodity production models to analyze the biophysical and economic consequences of alternative land use and land management patterns to achieve Total Maximum Daily Loads targets in a proto-typical agricultural watershed. We apply these models to find patterns that maximize water quality objectives for given levels of foregone agricultural profit. We find it is possible to reduce baseline watershed phosphorus loads by ~20% and sediment loads by ~18% without any reduction in agricultural profits. Our results indicate that meeting more stringent targets will result in substantial economic loss. However, when we add the social benefits from water quality improvement and carbon sequestration to private agricultural net returns we find that water quality improvements up to 50% can be obtained at no loss to societal returns. The cost of meeting water quality targets will vary over time as commodity and ecosystem service prices fluctuate. If crop prices drop or the value of ecosystem services increase, then achieving higher water quality goals will be less costly.

1. Introduction

Land-use and land-management (LULM) decisions are most often driven by private economic interests that do not necessarily align with the interests of society as a whole. Landowners earn financial returns by producing marketed goods (e.g., agricultural crops, timber) but not for producing non-marketed public goods (e.g., improving water quality, providing habitat for species, or sequestering carbon). As a result, landowner actions often deliver high levels of marketed goods but fail to provide the levels of water quality protection, species habitat protection, carbon sequestration, and other non-marketed ecosystem services that society desires (Polasky et al., 2011).

The U.S. Midwest agricultural landscape provides a prime example of this bifurcated production of goods and services. Income in 2012 from agricultural production in the 12 Midwestern states (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin) was $184 billion dollars (USDA ERS, 2013). These same 12 states also had 62,000 miles of rivers and streams on the impaired waters list and contributed an estimated 66% of the total nitrogen flux to the Gulf of Mexico (Alexander et al., 2007). Further, much of the carbon stored in Midwest soils has been reduced to historically low levels (Lal, 2002) and many of the region's songbirds already have trouble finding adequate habitat (Herkert, 1995). Unless incentives for farmers are changed, maximizing the Midwest's agricultural production values will remain the central goal for producers at the expense of environmental improvement.

In contrast, society has revealed that they are willing to pay for LULM patterns on landscapes that are more diverse and that deliver a healthier dose of non-marketed goods (Cho et al., 2008; Irwin, 2002; Sander and Polasky, 2009). For example, people are willing to pay for wetland protection and agricultural drainage programs that improve local water quality (e.g., Loomis et al., 1991). In addition, people are willing to pay for wildlife preservation measures taken by farmers (Brouwer and Slangen, 1998) and are willing to support soil conservation programs that protect local water quality (Colombo et al., 2006). Common to all of these cases is the willingness to sacrifice some market returns for some gains in environmental quality.

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From an economics perspective, the optimal tradeoff between a landscape's supply of market and non-market goods is produced by the LULM pattern that jointly maximizes marketed good value plus non-marketed good value or total good value. Here we present a method for finding the set of LULM patterns that maximize the joint production of marketed and non-marketed goods. We use an integrated biophysical-economic modeling approach to assess how alternative LULM decisions jointly affect agricultural crop production (marketed goods) and water quality (phosphorus and sediment loadings), carbon storage, recreation, and habitat provision (non-marketed public goods) in a proto-typical Midwestern watershed currently dominated by agricultural land use. An efficiency frontier is formed by a set of alternative LULM patterns that maximize landscape-level water quality production (a non-market good) over the range of landscape-level foregone production values (market goods). We create several efficiency frontiers. Some are formed assuming production value equals crop production value while others are formed assuming production value is the aggregate of crop production, carbon sequestration, and water quality improvement value (Polasky et al., 2008). Therefore, our approach presents policy makers with a framework to judge the cost-effectiveness of any LULM-based policy designed to meet water quality goals. The LULM pattern that is expected to emerge due to the policy can be evaluated by our biophysical-economic model and the resulting water quality improvement and economic cost values can be plotted against the efficiency frontier. The expected relative inefficiency of the policy is measured by its Euclidean distance to the frontier.

We apply our integrated biophysical-economic model to a typical Midwestern watershed currently dominated by agriculture. Our application produces the following results: First, the model suggests water quality can be modestly improved at little cost to the watershed's market economy if LULM is re-organized strategically. Second, while meeting more stringent water quality targets in the watershed will be costly in a conventional sense, the model suggests more stringent targets can be met at little social cost if we include environmental benefits in our value function before re-organizing LULM strategically. Finally, we can use the model to “score” the relative inefficiency of LULM-based policies by plotting the economic and environmental output of four watershed-level conventional water quality best management practices (BMPs) vis-a-vis the watershed's efficiency frontier.

2. Materials and Methods

2.1. Study Area

We apply our methods to the Minnesota River Basin's Seven Mile Creek watershed in south central Minnesota (Fig. A1). The application of our methods to a specific watershed allows us to illustrate how detailed modeling of LULM decisions and the consequent effects on water quality, ecosystem services, and economic returns can be used by policy-makers and other concerned citizens to identify LULM changes on the landscape that could improve the environment at least-cost.

Much of the Seven Mile Creek watershed is flat with poorly-drained soils. Subsurface drainage systems, however, have made the land highly productive; currently 83% of the watershed's area is in agricultural use. The upland portion of the watershed has an average slope of less than 1%. In the flat upstream portions of the watershed, agricultural runoff is the main source of sediment and nutrients. Downstream, near the confluence with the Minnesota River, the landscape is steeper with average slopes of approximately 20%. This steeper portion of the watershed includes ravines and failing streambanks that are important sources of sediment and phosphorus.

2.2. Defining a LULM Pattern

To analyze the effect of changes in LULM in the watershed on its economic and environmental performance, we changed baseline LULM in several hydrologic response units (HRUs) simultaneously. HRUs are irregularly shaped polygons defined by land use, soils, and slope classes. The Seven Mile Creek Watershed included 3262 HRUs with an average size of 2.8 ha (standard deviation 8.5 ha).

A set of simultaneous land use or management changes at the HRU-level formed an alternative LULM pattern. An HRU could be placed in any one of several LULM types. The alternative LULM types we considered are 1) typical baseline management with chisel and disk tillage; 2) conservation tillage, which has less efficient soil mixing and leaves more crop residue on the soil surface (30% residue cover at planting); 3) reducing phosphorus fertilizer application by 50% from current levels; 4) diverse grassland; 5) managed switchgrass; and 6) forest. Further, a HRU could remain in its baseline condition. Baseline LULM in each HRU was defined by the 2001 National Land Cover Dataset (NLCD) (Fry et al., 2009). The LULM typology was informed by local farmers and practitioners from the USDA Soil and Water Conservation District. Practitioners selected these LULM because 1) they are known to reduce sediment and P loss and 2) farmers in this landscape have experience implementing these LULM.

2.3. Sediment and Phosphorus Export Modeling

The Soil and Water Assessment Tool (SWAT 2005; Arnold et al., 1998; Gassman et al., 2007) is a watershed-scale model that functions on a daily time step. SWAT is primarily used to predict and evaluate land cover and land management impacts on the quantity and quality of water exported from watersheds dominated by agricultural land use. The model relies on environmental parameters and plant growth data to estimate the landscape contribution to stream flow and the delivery of sediment, nutrients, and pesticides to the watershed (Arnold et al., 1998; Arnold and Fohrer, 2005; Gassman et al., 2007). SWAT requires spatial information on soils, slope, and land cover. SWAT also requires daily data on precipitation, temperature, solar radiation, wind speed, and relative humidity. In addition to crop planting and harvest dates, the user must also provide management inputs such as the timing and extent of tillage practices and fertilizer application to simulate realistic plant growth and nutrient export from the watershed.

We generated daily SWAT outputs for each HRU in each of the 6 alternative LULM types over the 2001–2008 simulation period. We assumed all row crop LULM were in a corn-soybean rotation. This is consistent with planted acreage for Nicollet County, MN as well as local expert knowledge. Soils data was downloaded from SSURGO (USDA-NRCS, 2009). The landscape was segmented into three slope classes (0–2, 2–6, and >6%) based on a 10-m digital elevation model. Daily weather data across the landscape came from 2001 to 2008. Finally, we summarized SWAT's daily HRU-level output at the average annual level. Therefore, in the end, for each HRU – LULM combination we had an estimate of its average annual sediment and phosphorous export. More detailed description of model parameterization and calibration/validation performance is available in Dalzell et al. (2012).

2.4. Annual Agricultural Modeling and Economic Valuation

To calculate the annual per acre net returns to a LULM type that produces an agricultural product (all but LULM type 6 - forest) we multiplied the LULM's per acre annual yield of the associated crop times the market price of the crop and subtracted the crop's per acre annual production cost. We found the annual net return to agriculture for each HRU–LULM combination by multiplying the LULM's per acre annual net return and the HRU's area in acres (for the forestry LULM this value is 0 across all HRUs). Finally, watershed-level net returns to crop production under an alternative LULM pattern were found by summing all the HRU-level net returns generated under the LULM pattern.

To calculate marketable net returns in this analysis we needed price, yield, and production cost information on 1) corn with full fertilization and conventional tillage, 2) corn with reduced fertilization rates and