Optimal conservation tradeoffs: combining bi-level optimization with genetic algorithm methods

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We examine the spatial targeting of multiple management practices for the reduction of Nitrogen fertilizer runoff from agricultural production using an integrated modeling framework. These practices include reduced fertilizer application rates, conservation tillage, and land retirement. We characterize the non-point source pollution problem as a bilevel multiobjective optimization problem, which explicitly accounts for the nested nature of farm-level management decisions in response to prospective agri-environmental policy incentives. Our application considers the Iowa Raccoon Watershed, an intensive corn and soybean production region of the Upper Mississippi River Basin.

Introduction

- Agricultural runoff is a leading water quality stressor
- Integrated models that link management practices and production decisions to physical models of nutrient flow allow for evaluation of both the costs of conservation policies and the water quality benefits
- The problem of jointly minimizing the costs of practices and maximizing their benefits is nested: the solution management practice combinations that make up the Pareto optimal frontier will depend on how individual producers respond to policy incentives for each practice.

Objectives

1) Integrate the economic model of crop production with the SWAT model for the Iowa Raccoon Watershed
2) Use the integrated modeling system within the bilevel optimization framework to access the optimal tradeoffs between the costs and benefits of alternative conservation policies

Methods

We apply the bilevel optimization framework (Whittaker et al., 2016) to Iowa crop production data based on USDA GIS remote-sensing crop cover maps (Secchi et al., 2009). To account for producer spatial heterogeneity, we use a measure of soil productivity that comes from GIS-based soil data. We estimate the profit-maximizing response to prospective policy schemes, and then input the management practice and production decisions into a spatially explicit biophysical model to estimate the resulting environmental benefits. To model the natural system processes, we use the Soil and Water Assessment Tool (SWAT) hydrologic model calibrated and validated to the study watershed (Gassman et al., 2015). We use genetic algorithm methods to solve for the optimal policy combinations.

Bilevel multiobjective optimization problem

$$\max_{\tau,r,s,x_N} \; F(\tau,x,r,s) = \big(-C(\tau,r,s,x_N),\, B(r,s,x_N)\big)$$

$$\text{s.t.} \; (r^k,s^k,x_N^k) \in \underset{x^k,y^k,r^k,s^k}{\operatorname{argmax}} \{\pi^k(p^k,w^k,\tau^k):$$

$$(\tau^k,x^k,y^k,r^k,s^k) \in \Omega^k\}$$

$$\forall\, k \in \{1,\ldots,K\},$$

$$x_n^k \geq 0,\ \forall\, k \in \{1,\ldots,K\}, n \in \{1,\ldots,N\},$$

$$y_m^k \geq 0,\ \forall\, k \in \{1,\ldots,K\}, m \in \{1,\ldots,M\},$$

$$\tau_j^k \geq 0,\ \forall\, k \in \{1,\ldots,K\}, j \in \{1,\ldots,J\},$$

$$r^k \geq 0,\ \forall\, k \in \{1,\ldots,K\},$$

$$s^k \geq 0,\ \forall\, k \in \{1,\ldots,K\},$$

for policy scheme, τ, for land retirement, r, conservation tillage, s, and Nitrogen fertilizer use, x_N.

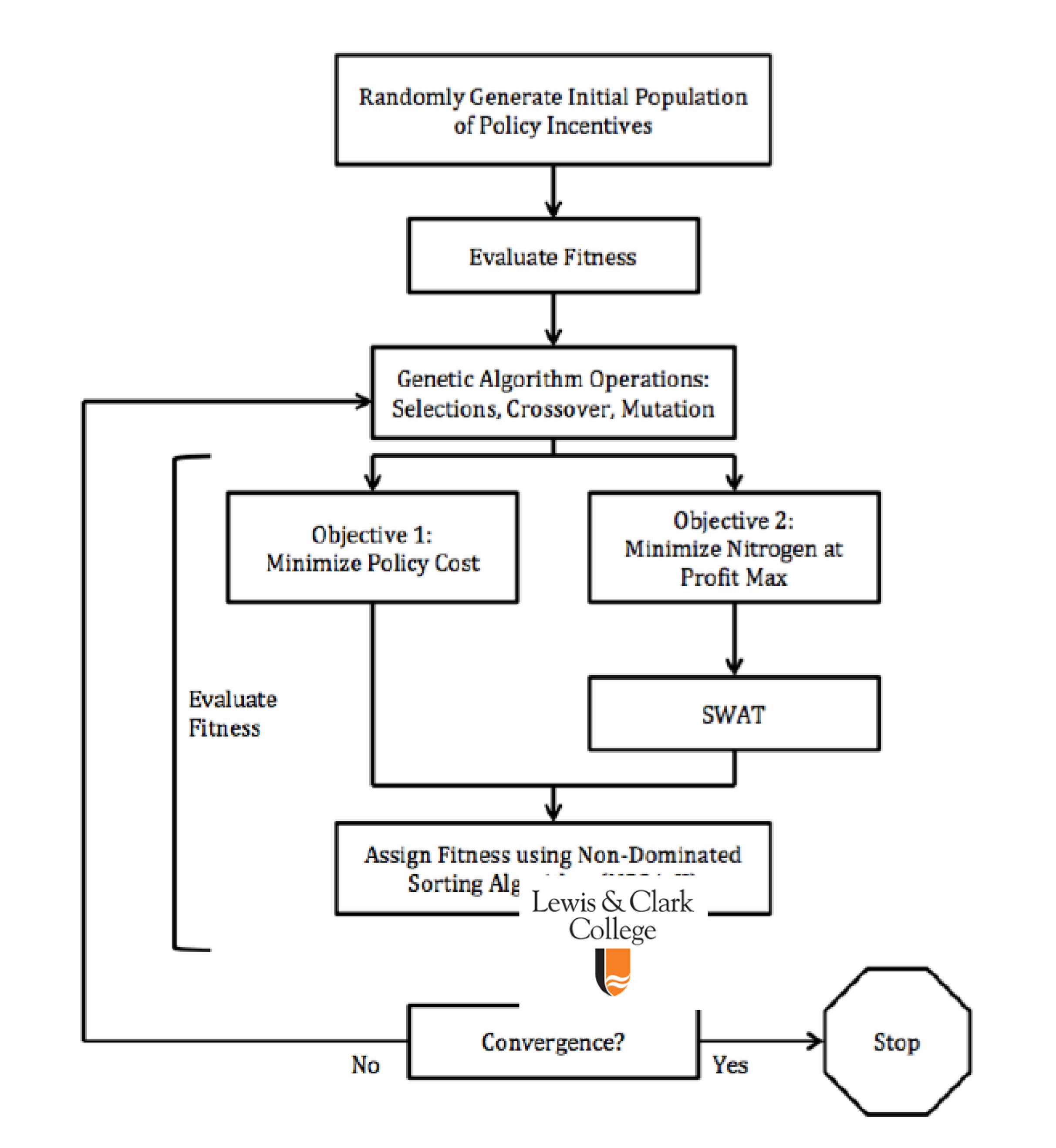
Profit maximization at the lower level

$$\max_{x^k,y^k,r^k,s^k} \pi^k(p^k,w^k,\tau^k) = p^k y^k - \sum_{n=1}^{N-1} w_n x_n^k - \tau_N^k w_N x_N^k + \tau_r^k r^k + \tau_s^k s^k$$

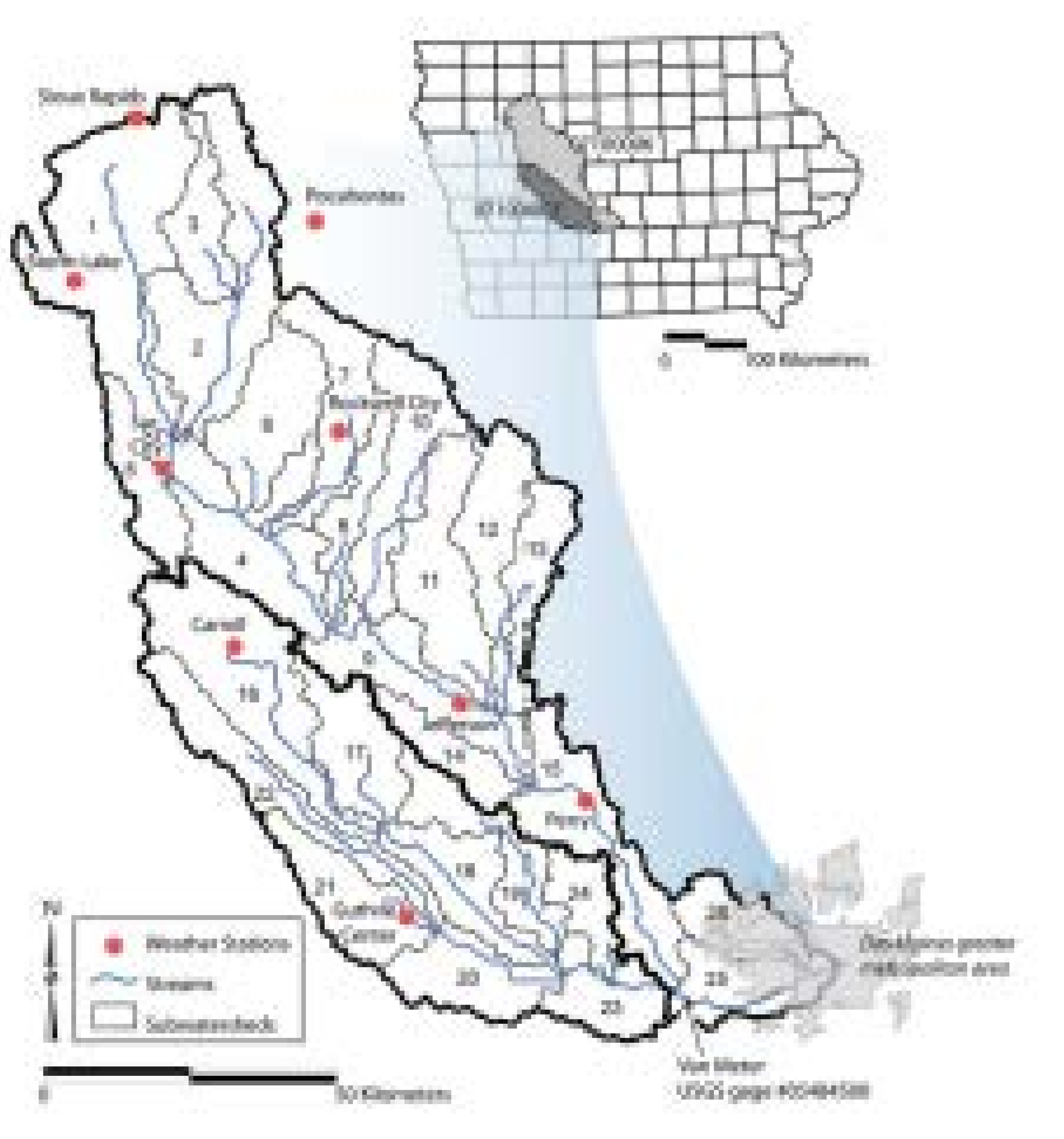
$$\text{s.t.} \quad y^k \leq f(x^k,r^k,s^k),$$

where x_N^k refers to the Nitrogen fertilizer input of producer k and $\tau = \tau_r, \tau_s, \tau_N$ is a policy vector including payments for land retirement (τ_r) and conservation tillage (τ_s), and a subsidy for fertilizer reduction, (τ_N).

The computational framework

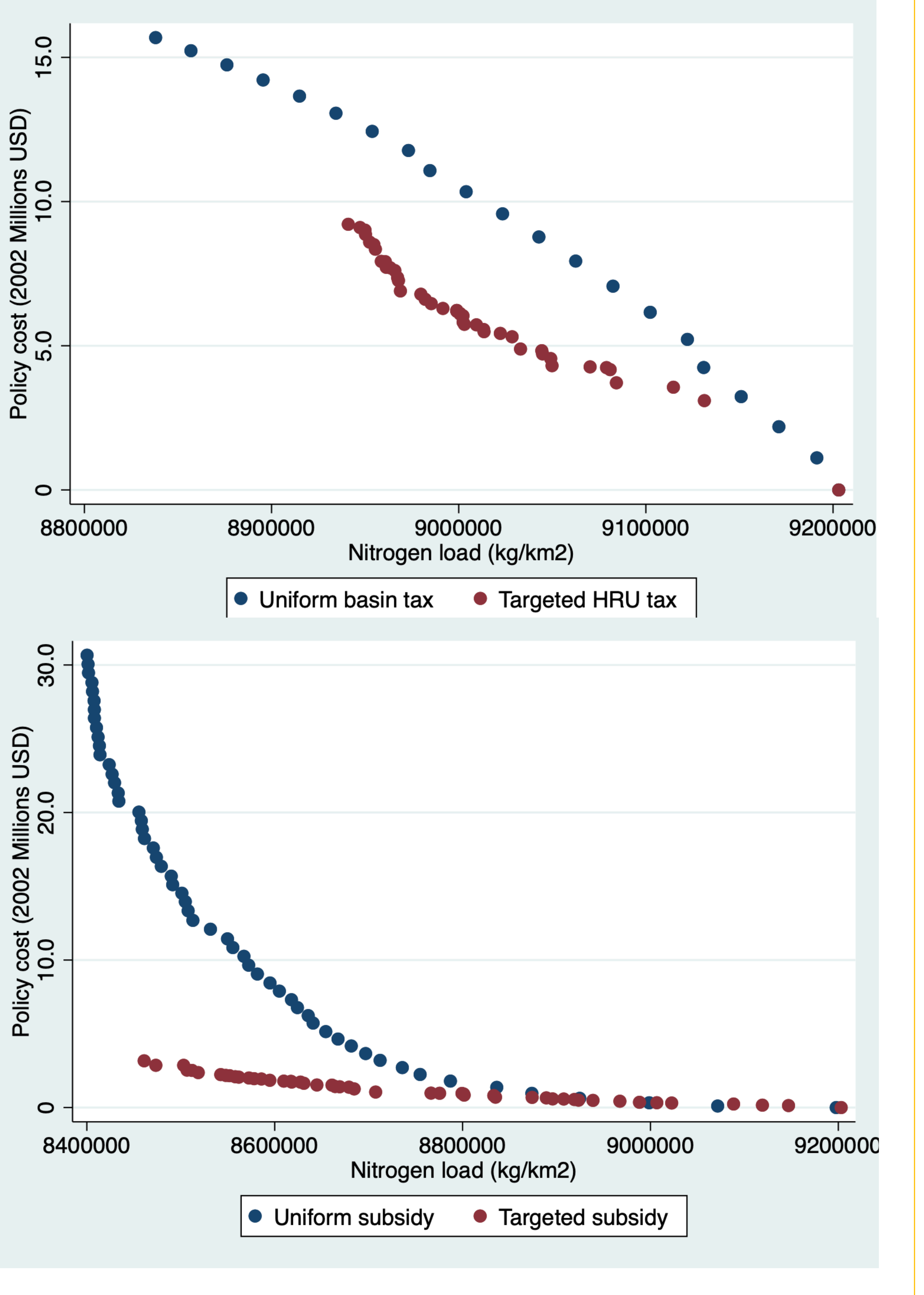


The SWAT delineation of the Raccoon River watershed (Jha et al., 2007)



Preliminary Results

- Two policies considered, fertilizer tax and no-till subsidies, produce vastly different results
- For both policies considered, fertilizer tax and no-till subsidies, we estimate significant inefficiencies of uniform basin policies, when compared to the targeted policies that vary by sub-basins
- The inefficiencies of uniform policies are especially pronounced for the lower nitrogen load reduction targets



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