Water Resources and Economics 11 (2015) 1–12

Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: www.elsevier.com/locate/wre

Valuing water quality tradeoffs at different spatial scales: An integrated approach using bilevel optimization

Moriah Bostian [a,*], Gerald Whittaker [b], Brad Barnhart [b], Rolf Färe [c], Shawna Grosskopf [c]

[a] Department of Economics, Lewis & Clark College, Portland, USA
[b] Agricultural Research Service (USDA), Corvallis, OR, USA
[c] Department of Economics, Oregon State University, Corvallis, USA

ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form
25 May 2015
Accepted 24 June 2015

Keywords:
Integrated modeling
Nonpoint pollution
Bilevel multiobjective optimization
Tradeoff analysis
Conservation targeting

ABSTRACT

This study evaluates the tradeoff between agricultural production and water quality at both the watershed scale and the farm scale, using an integrated economic-biophysical hybrid genetic algorithm. We apply a multi-input, multi-output profit maximization model to detailed farm-level production data from the Oregon Willamette Valley to predict each producer's response to a targeted fertilizer tax policy. Their resulting production decisions are included in a biophysical model of basin-level soil and water quality. Building on a general regulation problem for nonpoint pollution, we use a hybrid genetic algorithm to integrate the economic and biophysical models into one bilevel multiobjective optimization problem, the joint maximization of farm profits and minimization of Nitrate runoff resulting from fertilizer usage. This approach allows us to more fully endogenize fertilizer reduction cost, rather than assume an average cost relationship. The solution set of tax rates generates the Pareto optimal frontier at the watershed level. We then measure the tradeoffs between maximum profit and Nitrogen loading for individual farms, subject to the solution fertilizer tax policy. We find considerable variation in tradeoff values across the basin, which could be used to target incentives for reducing Nitrogen loading to agricultural producers under non-uniform control strategies.

1. Introduction

Nutrient runoff from agriculture is a leading contributor to water quality impairment, inland eutrophication, and coastal hypoxia. The integration of biophysical models of these processes with economic models of agricultural producer behavior constitutes an important area of research related to nonpoint pollution policy. Examples of integrated economic and biophysical models for agriculture include modeling the biophysical outcomes of alternative economic scenarios [55,34] or the solution to a single-objective economic optimization model [52,65] and linking both single and multiobjective economic optimization models to biophysical models in a model chain [31,38,40,70,67,46,29].

In the model chain approach, information passes only in one direction, so that the optimal decision at any point in the chain is constrained by any previous decisions or outcomes in the chain. A simultaneous optimization of all objectives can inform the calculation of tradeoffs between multiple objectives. Several studies employ genetic algorithms to simultaneously optimize multiple objectives by allowing information to pass between each objective in both directions [7,2,44,45,47]. These studies illustrate the use of genetic algorithms to calculate the Pareto optimal frontier for both economic and environmental objectives.

We build on the use of genetic algorithms for nonpoint pollution policy analysis by integrating a realistic biophysical model with a detailed economic optimization model that more fully endogenizes each producer's response to the search for an optimal targeted nonpoint pollution policy. Our use of genetic algorithm computation methods to more freely integrate the economic and biophysical models is detailed in a related study of targeted policy design [73].

Our approach contributes to existing work on integrated modeling for nonpoint pollution in several important ways. First, we include both a detailed, spatially explicit biophysical model and a complete model of profit maximization, with minimal restrictions to solution values and without imposing an *a priori* production technology relationship. Second, we apply an adaptive modeling framework to allow for two-way feedback between our economic and environmental objectives. We formulate our multiobjective optimization as a bilevel optimization problem, which we show is amenable to the more general regulation problem underlying much of the nonpoint policy literature. This framework

* Corresponding author.
E-mail address: mbbostian@lclark.edu (M. Bostian).

http://dx.doi.org/10.1016/j.wre.2015.06.002
2212-4284/

endogenizes fertilizer usage, making economic cost endogenous and better updating the search for an efficient allocation of fertilizer reduction. The resulting policy generates a set of Pareto optimal tradeoffs that can be evaluated across objectives. Third, we evaluate the resulting tradeoffs at varying spatial scales, for individual producers and for the basin as a whole.

This integrated economic-biophysical model simulates a rich set of agent-level decisions, made in response to the Pareto optimal policy, and corresponding environmental outcomes that can be used to evaluate tradeoffs at the individual level. We examine these decisions for a set of grass seed farms situated in the Calapooia River watershed, a predominantly agricultural watershed in Oregon's Willamette Valley. We also make use of detailed micro-level farm production data, which further enhances the evaluation of individual tradeoffs between farm profit maximization and watershed Nitrogen loading.

To value these tradeoffs, we jointly model profit-maximizing crop production and Nitrogen loading levels, simulated by the economic-biophysical model, as outputs in a production process using the directional output distance function [10]. In economic production theory, the directional output distance function is dual to the revenue function, which we exploit to derive shadow price estimates for Nitrogen loading in the basin [5,19,20].

We find that the tradeoff between farm profit and Nitrogen loading varies greatly across farmers in the watershed, due to differences in farm productivity and location in the basin's hydrologic network. This general result is consistent with previous studies that consider environmental heterogeneity from the nonpoint pollution literature [30,53,54]. In practice, managers could use this information to target incentives for fertilizer reduction or reduced Nitrate runoff, such as easement payments or funding for best management practices, to farms that have a lower opportunity cost of reducing eventual Nitrogen loading in the basin. Randhir and Shriver [48] demonstrate the potential gains from using multi-attribute shadow price values to target restoration incentives across a watershed.

Moreover, analysis of the tradeoff at the farm level offers a better picture of the distribution of costs across producers in the region, which could be added to existing information on environmental heterogeneity. This spatial distribution may be of concern for equity considerations and could affect the feasibility of implementing prospective agri-environmental policies in practice. For instance, variation in compliance costs across producers is a form of heterogeneity that could undermine ambient pollution policies targeted at the group level [61,63]. Differences in tradeoff values at the farm level could also help us to explain why some producers participate in voluntary management practice programs while their neighbors opt out, as well as identify areas where uniform policies are likely to generate large efficiency losses [30,69,54].

2. Background on nonpoint source pollution

Information asymmetries between producers and regulators, as well as uncertainty regarding individual emissions, complicate nonpoint source pollution policies for agriculture [75]. As a result, common output-oriented policy options, including Pigouvian taxes and output quantity standards, can no longer be generally expected to generate efficient pollution levels. Two key early insights motivate much of the related literature. First, while individual emissions levels may be unknown, the use of polluting inputs, such as fertilizer and pesticides, can be more easily observed [26]. This gives rise to greater focus on input-oriented policy instruments and extensions to management practices on the farm [49]. Second, while farm-level emissions may not be directly observable, ambient pollution levels can be monitored at regional receptor sites. It may still be possible to use group-level policies directed to ambient pollution concentrations to indirectly target individual emissions and achieve a desired pollution level [56,57,68,61,62].

2.1. Biophysical models and nonpoint policy

Biophysical models that account for factors such as hydrology, soil drainage, and climate, can serve to narrow the information gap for nonpoint source pollution, by identifying the relationship between input use, nutrient runoff, and ambient concentration levels. Understanding this relationship is particularly important for policy targeting and policy tradeoff analysis.

Numerous studies link agricultural production to a biophysical model, commonly using linear programming methods to estimate the resulting policy tradeoffs between emissions reductions and production value. Important innovations include the introduction of dynamic optimization for fertilizer and irrigation timing decisions [35,36,66]; the use of cost-effectiveness and the theory of second best for policy comparison [30,37]; incorporating producer heterogeneity [30,24,66,53,54,74]; allowing for stochastic processes in an ambient tax scheme [56,9,32]; allowing for substitution effects in response to input-oriented policies [33,39]; and the use of evolutionary algorithms to simultaneously optimize over production and water quality objectives [7,2,44,45,47].

Examined policy instruments include fertilizer input taxes [35,12,30,25,39]; quantity controls for fertilizer and irrigation [66], irrigation fees [36]; emissions taxes [69,36]; drainage standards [69]; emissions standards [53]; management practice standards [54]; and voluntary-threat approaches [56,57,68,62].

Across policy instruments, spatial heterogeneity emerges as an important factor in the relative inefficiency of alternative policy options [30,69,53,54]. Differences in soil quality, topography, farm productivity and location in the hydrology network affect key determinants, such as plant nutrient uptake, drainage rates, compliance costs and pollution transfer coefficients. In general, uniform approaches, whether in the form of standards, fees, or management practices, impose higher costs than alternatives that incorporate heterogeneity in some form. We build on this area of the literature by considering heterogeneity at the farm level, in both the production technology and biophysical characteristics, and then evaluating policy tradeoffs at both the farm level and for the basin as a whole. We briefly describe the nonpoint pollution problem in our study below, and outline our multiobjective policy analysis framework in the next section.

2.2. Nitrogen loading in the Calapooia River Basin

Our study area, the Calapooia River Basin, lies just west of the Cascades Mountain range, in the Oregon Willamette Valley. Agriculture comprises the majority of land use, and though small in size, this watershed accounted for roughly 40% of all perennial ryegrass production in the United States during our study period. Perennial ryegrass production is relatively fertilizer-intensive, and this area is known (at least locally) as the "grass seed capital of the world."

The environmental effects of agricultural land use in the Calapooia have been previously studied as part of the USDA Conservation Effects Assessment Project (CEAP) [15,41]. A recent National Water Quality Assessment of the watershed identifies Nitrate Nitrogen as a particular concern, due to the increasing trend of stream and groundwater concentrations in excess of human health and aquatic life standards [41,18]. Recent sampling confirms that these Nitrogen concentrations vary greatly across the basin, even for areas with over 90% of land in agriculture [41], making this a particularly interesting case to consider for spatial heterogeneity and policy targeting.