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COST-EFFECTIVE PLACEMENT OF BEST MANAGEMENT PRACTICES IN A WATERSHED: LESSONS LEARNED FROM CONSERVATION EFFECTS ASSESSMENT PROJECT[1]

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ABSTRACT: This article reviews the key, cross-cutting findings concerning watershed-scale cost-effective placement of best management practices (BMPs) emerging from the National Institute of Food and Agriculture Conservation Effects Assessment Project (CEAP) competitive grants watershed studies. The synthesis focuses on two fundamental aspects of the cost-effectiveness problem: (1) how to assess the location- and farmer-specific costs of BMP implementation, and (2) how to decide on which BMPs need to be implemented and where within a given watershed. Major lessons learned are that (1) data availability remains a significant limiting factor in capturing within-watershed BMP cost variability; (2) strong watershed community connections help overcome the cost estimation challenges; (3) detailing cost components facilitates the transferability of estimates to alternative locations and/or economic conditions; and (4) implicit costs vary significantly across space and farmers. Furthermore, CEAP studies showed that (5) evolutionary algorithms provide workable ways to identify cost-effective BMP placements; (6) tradeoffs between total conservation costs and watershed-scale cost-effective water quality improvements are commonly large; (7) quality baseline information is essential to solving cost-effectiveness problem; and (8) systemic and modeling uncertainties alter cost-effective BMP placements considerably.

(KEY TERMS: BMPs; watershed management; water quality economics; optimization; cost-effective BMP placement; costs of BMPs; evolutionary algorithms.)

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INTRODUCTION

Agricultural production is prone to generating nonpoint source pollution such as nutrient and pesticide runoff, erosion, and leaching. Curbing and preventing water quality problems associated with nonpoint sources remain one of the imposing policy challenges faced by agriculture (Ogg and Keith, 2002; Claassen, 2009; Lichtenberg *et al.*, 2010). Most water pollution reduction programs in the United States (U.S.) targeted at agriculture are voluntary in that they offer financial and technical assistance to land operators for the adoption and use of cropland conservation and land management practices, commonly referred to as the best management practices (BMPs). Designing the programs in a cost-effective way, that is, focusing limited program resources on the farmers and the BMPs that provide the most water quality improvement per program dollar is becoming an ever more important practical issue with the conservation budgets being increasingly tightened at local, state,

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and federal levels (Shortle *et al.*, 2012). The growing attention to cost-effectiveness of achieving water quality improvements is exemplified by the recent interest in water quality trading that involves nonpoint sources (Horan and Shortle, 2011; Kling, 2011; Newburn and Woodward, 2012; Shortle *et al.*, 2012). Although water quality trading and other alternatives that combine regulatory and voluntary approaches to agricultural pollution have been actively discussed and promoted by different government agencies (Ogg and Keith, 2002), voluntary programs relying on BMP payments remain the backbone of pollution control policies in U.S. agricultural-dominated watersheds (Claassen, 2009; Kling, 2011).

A standard approach to cost-effective policy (e.g., Babcock *et al.*, 1996) assumes that a conservation planner, such as a government agency or a nonprofit group, has set aside a certain amount of funding for a conservation program. A further assumption is that commercial farmers are mostly motivated by profit concerns in the choice of management practices and will adopt the BMPs if the payments offered by the planner are equal to or exceed the opportunity costs of adopting the BMPs. An important question then is how to prioritize, that is, selectively offer program funds to farmers in the watershed in exchange for the adoption of BMPs. In other words, which BMPs at which locations should receive payments so that society gets the best water quality improvement possible, given the program's budget? In economics terminology, the allocation of funds and the corresponding placement of BMPs in the watershed achieved through such a program is called cost-effective, if maximum water quality improvement is achieved within the program budget.

The problem of designing and implementing watershed-scale cost-effective conservation programs remains a daunting task for a number of reasons, including the high costs associated with the policy maker's need to know location-specific benefits and costs of the BMPs (Horan and Shortle, 2011). The costs of BMP implementation are commonly farm-specific and reflect not only the natural farming conditions such as soil type, landscape, and weather but also the personal values and attitudes toward profits, risks, and the environment, which may vary significantly among farm operators (Gelso *et al.*, 2008; Prokopy *et al.*, 2008). Pollution emissions from agricultural fields are largely inestimable and stochastic due to weather events that affect the fate and transport of pollutants via runoff, leaching, or volatilization. In addition, the effectiveness of various BMPs for controlling water pollution is not fully understood as it varies with landscape, soil type, topography, climatic factors, cropping patterns, and farming practices (Rittenburg *et al.*, 2015). Consideration of the watershed, rather than edge-of-the-field scale necessitates the need to know complex pollutant transport processes and the interdependent effects of BMPs placed on different sites within a watershed (Veith *et al.*, 2003; Gitau *et al.*, 2004). The delayed response of water quality to practice implementation and historical legacies of past erosion further complicate the assessment of water quality benefits of BMPs (Tomer and Locke, 2011).

To improve the understanding of how to optimally locate and sequence the placement of BMPs within a watershed to achieve water quality improvement goals, the National Institute of Food and Agriculture — Conservation Effects Assessment Project (NIFA-CEAP) and the USDA Natural Resources Conservation Service (NRCS) jointly funded 13 competitive grant projects across the U.S. to investigate the linkages between various BMPs, and the resulting effects on water quality. The projects were competitively awarded in 2004-06 among the watersheds that had large, long-term datasets available at the time of application (Table 1). The fundamental goals of most of these projects, referred to as CEAP projects in this article, included the exploration of the economic and social factors related to adoption and proper maintenance of conservation practices, and identification of optimal placements of practices within the watersheds (Duriancik *et al.*, 2008).

A number of studies have summed up the various CEAP projects' results: NRCS (2004), Duriancik *et al.* (2008), the special November/December 2010 issue 65(6) of the *Journal of Soil and Water Conservation* dedicated to the CEAP competitive grant watershed projects, and Osmond *et al.* (2012a, b). Several CEAP projects' lessons related to economic and social factors affecting adoption and use of BMPs were summarized by Hoag *et al.* (2012). These authors noted that the chances of BMP adoption increase if, among other things, the results of the implementation are visible on the farm, support for implementation is available from local, trusted networks of other farmers, conservation professionals, and agribusinesses, and when farmers feel that they are in control of BMP implementation. One of the major findings by Hoag *et al.* (2012) is that in most instances BMPs would not be adopted if the farmers' costs of implementation were not equal to or exceeded by the financial benefits coming from the changed farm profitability and/or cost share and other monetary incentives. Building on this observation, and supplementing the Hoag *et al.* (2012) study's focus on individual producers, this article reviews the cross-cutting findings of the CEAP projects that have not been previously synthesized — those related to the watershed-scale cost-effective placement of BMPs. The synthesis focuses

TABLE 1. Evaluation of BMP Costs and Cost-Effectiveness in CEAP Projects. Check marks indicate the SPECIFIC aspects of the cost-effectiveness analysis addressed in the listed studies.

			BMP Costs				**Cost-Effectiveness Analysis**		
CEAP State, Project Years	**Watershed**	**Study**	**Estimates Attained**	**Explicit Factors**	**Implicit Factors**	**Benefit-Cost Analysis**	**Estimates Attained**	**Tradeoffs**	**Methods**
New York, 2005-2010	Cannonsville Reservoir	Rao *et al.* (2012)	✓	✓		✓			
Kansas, 2006-2011	Cheney Lake	Langemeier *et al.* (2010)	✓			✓			
Indiana, 2006-2011	Eagle Creek Watershed	Oliver (2008)	✓			✓	✓	✓	✓
		Prokopy *et al.* (2008)			✓				
		Reimer *et al.* (2012a)			✓				
		Reimer *et al.* (2012b)			✓				
Missouri, 2005-2010	Goodwater Creek Watershed	Intarapapong *et al.* (2008)	✓	✓					
Arkansas, 2005-2010	Lincoln Lake	Rodriguez *et al.* (2011a)	✓			✓			
		Rodriguez *et al.* (2011b)	✓	✓		✓	✓	✓	✓
Utah, 2004-2009	Little Bear River	Jackson-Smith and McEvoy (2011)			✓				
Georgia, 2005-2010	Little River	Jang *et al.* (2013)	✓						
Oregon, 2006-2011	Lower Calapooia River	Whittaker *et al.* (2009)							✓
Idaho, 2004-2008	Paradise Creek	Tosakana *et al.* (2007)	✓	✓		✓	✓	✓	
		Tosakana *et al.* (2010)		✓	✓				
Pennsylvania, 2006-2010	Spring Creek	Brooks *et al.* (2011)			✓				
		Armstrong *et al.* (2012)			✓				
Iowa, 2004-2008	Walnut Creek and Squaw Creek	Rabotyagov *et al.* (2010a)	✓			✓	✓	✓	✓
		Rabotyagov *et al.* (2010b)	✓			✓	✓	✓	✓
		Kling (2011)							✓

on two fundamental aspects of the cost-effectiveness problem: (1) how to assess the location- and farmer-specific costs of BMP implementation, and (2) how to decide which BMPs need to be implemented and where within a given watershed so that a given water quality goal is achieved with the lowest possible policy outlay or the most improvement in water quality is attained from a given conservation program budget.

The article is organized as follows. After presentation of a formal set up of the cost-effective placement problem, the major concepts used throughout the study are explained, and the sources of information for the study are detailed. Next, the lessons learned from the CEAP studies concerning the costs of BMPs and the identification of cost-effective practice placements are presented. The last section summarizes and identifies future research needs.

COST-EFFECTIVE CONSERVATION PROGRAM

To formally introduce the concept of a cost-effective conservation program, assume that a watershed is divided into sites (tracts of land), on each of which alternative, mutually exclusive BMPs (or mutually exclusive suites of BMPs) could be implemented. The water quality improvement benefit of implementing BMPs is assumed to be a function of watershed characteristics, climatic conditions, and, importantly, of land areas devoted to the specific BMPs on the specific sites. Any collection of location-specific BMPs represents a conservation plan. It is further assumed that the per-acre costs of BMP adoption are known to a conservation planner for all the sites in the watershed and all the potential BMPs under consideration. Then the total cost of a conservation plan is given by the products of per-acre costs and the areas under the plan's BMPs, summed over all the acres on which the BMPs are implemented. Ideally, the conservation planner would place the BMPs so that the total benefit — water quality — is maximized and the cost — the total cost of implementing the BMPs — is minimized. Therefore, two interrelated problems are considered — maximizing water quality subject to a given cost constraint, or the counterpart problem of minimizing the cost of achieving a given water quality target. Both problems are referred to as cost-effectiveness analysis (CEA) in environmental economics.

Note that the CEA setup considered here is restricted to the BMPs that could be reasonably considered as area-determined and location-specific, such as riparian buffers, conservation tillage, or grassed waterways. The framework would need to be modified for consideration of livestock-operation BMPs, such as those associated with changes in animal rations, especially when animals are allowed to move freely across tracts of land. Several other important concepts and assumptions underlying the CEA setting are discussed in detail below.

BMP Costs

The assumption that the costs of BMP implementation are known is in fact a very strong assumption. The notion of cost is well developed in economic theory, but the concept is much harder to capture empirically. CEA requires the estimates of opportunity costs of BMPs, that is, the estimates of what farmers *need to give up* to install and maintain BMPs. The distinction of who bears the cost (farmer, society as a whole/taxpayers through government subsidized programs, taxpayers in a certain state if a program is subsidized by the state, etc.) is of secondary, yet still significant, importance. The greatest difficulty with estimating costs empirically is that most of the time the BMP costs are location-, time-, and farmer-specific. Therefore, BMP costs can be affected by changing economic conditions, policies, education, location, and outreach programs (Pannell *et al.*, 2006).

Based on the relative ease of estimation in dollar terms, the present discussion of CEAP findings distinguishes between two generic components of the overall costs, explicit and implicit. Explicit costs include estimates based on corresponding engineering specifications, such as installation and maintenance costs. These costs are commonly labeled "engineering" in economic assessments (e.g., Lubowski *et al.*, 2006). Explicit costs also include the opportunity cost of the land taken out of production that could be measured via the corresponding foregone production net returns (economic benefits minus costs).

In contrast, implicit costs are much harder to express in dollar terms. Implicit costs include those stemming from the hesitancy of a farmer to make irreversible investments in the face of uncertainty and the desire to retain options for future land-use decisions (Schatzki, 2003). An aversion to risk may mean that farmers would not change the current, known practices to the new ones even if the expected net returns are greater, but there is perceived or true uncertainty about the net returns (Parks, 1995). The cost of learning about an unfamiliar BMP is also an implicit cost (Pannell *et al.*, 2006). Depending on the farmer's socioeconomic characteristics such as age, education, income, involvement in local affairs, etc., and the BMP in question, the cost of learning could be as low as spending an hour on the extension website or as high as dedicating a tract of land to try the practice for several years without the expectation of immediate economic returns. Empirically, the impact of a factor contributing to the implicit costs is commonly quantified via statistical models which predict how much the probability of the BMP adoption changes with the change in the variable representing the factor (Soule *et al.*, 2000; Prokopy *et al.*, 2008).

Baseline

The implementation of BMPs is aimed at improving water quality relative to a known baseline. Conceptually, baseline is the set of conditions that would have occurred in the absence of the conservation program in question, that is, the set of preexisting conditions against which new-BMP-induced water quality improvements are measured or modeled. The baseline set of conditions encompasses all the multiple factors that influence water quality in the watershed and include land use (e.g., location of cropped land, pastures, forests, or urban development), cropping or grazing patterns (e.g., crop rotations, amount of livestock, periodicity of grazing), predominant weather conditions, preexisting farming practices including BMPs (e.g., fertilizer application rates, existing riparian buffers, predominant tillage practices), and the water quality itself. Since such vast amount of information is rarely possible to obtain for large watersheds, the baselines in watershed-scale CEA studies usually combine observational and modeled data (Veith *et al.*, 2003; Yang *et al.*, 2005; Cattaneo *et al.*, 2005; Helmers *et al.*, 2007; Horan and Claassen, 2007; Claassen *et al.*, 2008; USDA/NRCS, 2012).

The importance of correctly identified baselines for cost-effective policies has been recognized in the literature. Shortle *et al.* (2012) note that incorrect baselines may result in the payments to farmers in excess of their opportunity costs or not provide any additional water quality improvement. Because of the data limitations and modeling involved, estimating a baseline is a difficult task by itself (Jha *et al.*, 2006; Claassen *et al.*, 2008; Baker, 2011). In fact, one of the important goals of the companion of the CEAP-NIFA projects, the CEAP Cropland National Assessments project, was to estimate a current BMP baseline using a national farmer survey (Lambert *et al.*, 2007).

Identification of Watershed-Scale Cost-Effective BMP Placements

There is a sizable economics literature on BMP cost-effectiveness at a field or farm scale (see, e.g., review by Shortle and Horan, 2001). However, reflecting the difficulty of modeling watershed-scale rather than edge-of-the-field BMP effectiveness, early cost-effectiveness studies have commonly relied on overly simplified water quality models in which watershed-scale effects of BMPs were assumed to be proportional to edge-of-the-field effects (e.g., Babcock *et al.*, 1996). With such models, solving the CEA problem does not present any computational difficulties. In contrast, the use of more realistic, complex water quality models typically greatly complicates the identification of cost-effective BMP placement. If one could estimate the benefits and costs of all potential BMP placements, solving the CEA problem would be simple. However, in reality, such an approach is rarely feasible because of the combinatorial number of the placements to evaluate. One remedy in this case has been in replacing the CEA problem with a benefit-cost analysis (BCA). The BCA in this setting is the problem of evaluating the costs, water quality benefits, and, sometimes, measures of variation in costs and/or benefits, for a predetermined set of BMP placements, usually referred to as scenarios. The scenarios are often chosen based on external information such as expert opinion or planner and/or farmers' preferences. The comparison of the scenarios using a set of metrics may or may not lead to a clear ranking of the scenarios. While BCA is not a complete CEA, it could be considered as a precursor of CEA and commonly provides very valuable information for further analysis and discussion.

Several CEAP teams embraced another, recently introduced remedy for the CEA in the case of a large number of BMPs and a realistic water quality function, which comes with the use of evolutionary algorithms (EAs). The EAs are stochastic tools that provide methodological ways to search through large numbers of possibilities by attempting to mimic the process of biological evolution. The EAs have only recently begun to be applied to integrated watershed modeling systems (Srivastava *et al.*, 2002; Veith *et al.*, 2003).

Uncertainty

Scientific uncertainty is a big part of all components and stages of CEA (Secchi, 2013). The uncertainty about opportunity costs of BMPs has been well recognized as a problem in economic assessment of BMPs (Cattaneo *et al.*, 2005; Kennedy and Wilson, 2009). Even when observed data are used to construct baselines, sampling of large watersheds results in baseline uncertainty (USDA/NRCS, 2012). The challenges in accessing BMP effectiveness and the approximate nature of EAs likewise contribute to the overall CEA solution uncertainty.

There is a sizable economics literature dealing with policy making under uncertainty, but both theoretical and empirical questions remain. In the water quality context, the problem of cost-efficiency of achieving probabilistic pollution reduction targets has been studied both theoretically and empirically, albeit with simplified water quality models and under restrictive assumptions about the distribution of the achievable pollution reduction. Shortle and Horan (2001) provide a review of the studies that analyzed the problem of minimizing the cost of achieving a given water quality target with a specified level of confidence.

SOURCES OF INFORMATION ABOUT THE CEAP PROJECTS

This article relied on the information shared by the CEAP project teams during watershed site visits that occurred near the completion of each CEAP project. Additional data were gathered by reviewing the final project results available at the USDA's Current Research Information System web page (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/ceap/?&cid=nrcs143_014164, accessed August 2013). When needed, the major agricultural economics database AgEcon (http://ageconsearch.umn.edu, accessed August 2013) was checked for reports, conference papers, and similar publications. For simplicity, the individual CEAP projects are referred to by the abbreviated name of the state in which the study watershed is located. The characteristics of the 13 watersheds such as water resource name, pollutant(s) of concern, land use, and watershed area are detailed in Osmond *et al.* (2012b, table 1), the BMPs evaluated are summarized in Osmond *et al.* (2012a, table 3.1), and the hydrological models used (when applicable) are specified in Osmond *et al.* (2012a). NE CEAP and OH CEAP did not have economics components. Brief summaries of the CEAP economics studies referenced in this article are provided in the Appendix and in Osmond *et al.* (2012a).

RESULTS AND DISCUSSION

Various versions of the BMP cost evaluations, BCAs and/or CEAs were incorporated into the majority of the CEAP projects (Table 1). Our discussion proceeds from the synthesis of the CEAP project findings relating to the costs of BMPs to the lessons learned concerning the identification of the economically optimal BMP placements.

Costs

Most CEAP studies attained BMP cost estimates, and many analyzed the explicit and implicit components (Table 1). The estimates have been developed for barnyard improvements and riparian buffers (NY CEAP); varying versions of conservation tillage (KS CEAP); cropland protection, conservation tillage, contour farming, conversion to forest, conversion to wetland, nutrient management, terraces and diversions, vegetative buffers, waste management, runoff control (IN CEAP); grassed waterways (MO CEAP); suites of BMPs which included optimal grazing and a buffer and differing poultry litter application rates, timing, and litter characteristics (AR CEAP); terraces and grassed waterways (GA CEAP); tillage practices, land retirement, gully plugs and buffer strips (ID CEAP); and BMP suites which included alternative conservation tillage systems, contour farming, grassed waterways, terraces, reduction in nitrogen fertilizer applications, and land retirement (IA CEAP).

Several important lessons emerge from the projects' experiences. The first and perhaps most significant lesson is that developing cost data is costly. Most studies spent significant resources on attaining the estimates, as there is no nation-wide source of cost data presently available to researchers or conservation planners. Although state-average engineering costs in general are accessible via the cost-share rules and protocols employed by NRCS, these were of limited use for the studies that needed to capture within-watershed cost variability for watersheds that were contained in their entirety within the corresponding state's boundaries. Developing regional or even nation-wide BMP cost databases would be welcomed by both the research and policy communities as such data would significantly reduce the resources needed for future CEA studies and assessments.

A second lesson is that local farmer and conservation community connections matter. The projects that were successful in developing location-specific estimates had consistently strong and trusting connections with farmers, local NRCS personnel, Soil and Water Conservation Districts, and local farmer organizations. Similar importance of local connections for securing high rates of famer participation in water quality trading program has been recently underscored by Newburn and Woodward (2012).

A third lesson is that reporting detailed cost component data facilitates the transferability of estimates. Most of the projects that attained cost estimates provided detailed descriptions of the data construction. Several projects went further and documented components of the explicit costs. For example, the MO CEAP (Intarapapong *et al.*, 2008) provided detailed information on the cost computation formulas together with production input price data that went into estimation of net returns with and without grassed waterways. Such detailed data descriptions allow estimation of similar BMP costs at other time periods when, for example, crop, fertilizer, or energy prices change. While the dependency of the BMP costs on location and topography has been recognized for a long time (see e.g., the review by Lichtenberg *et al.*, 2010), the dependency on crop and production input prices has drawn the researchers' attention only recently. Notably, Reimer *et al.* (2012b) comments that farmers surveyed about the use of BMPs in the IN CEAP watershed mentioned the changes in crop prices and production inputs among the factors influencing the decisions on BMP adoption.

The NY CEAP (Rao *et al.*, 2012) reported the costs broken down into installation, maintenance, and loss of income due to the land taken out of production. In absence of otherwise good estimates, one can transfer the NY BMP costs to other locations by using, if applicable, the same installation costs, adjusting the maintenance costs in accordance with the local wages and/or fuel prices, and adjusting the opportunity cost of land removed from production upward or downward depending on whether the land in question is more or less productive than that studied in Rao *et al.* (2012).

Another argument for careful consideration of the various components of BMP costs is implied by the findings of the ID CEAP (Tosakana *et al.*, 2010). Their survey of over 1,500 farmers in the Northwest found that the surveyed farmers viewed maintenance costs of gully plugs and buffer strips as more important than the corresponding installation costs. This finding on importance of maintenance costs is echoed in the UT CEAP study Jackson-Smith *et al.* (2010) which estimated that a sizable proportion of BMPs may not be properly maintained. It remains to be investigated how transferable these findings are to other geographic regions and/or long-term BMP. However, if the perception of greater importance of maintenance *vs.* installation costs turns out to be widespread, the two cost components may need to be treated differently by conservation program planners for the programs to be designed cost-effectively.

A fourth lesson is that implicit costs vary significantly across space and farmers. The IN CEAP (Prokopy *et al.*, 2008) synthesized 55 recent studies on the determinants of BMP adoption that impact the implicit, farm- and farmer-specific costs. Using the vote count methodology, the study identified important farmer characteristics reflecting capacity, attitudes, and environmental awareness, as well as farm characteristics that were consistently found to impact adoption of BMPs.

A relatively little studied aspect of implicit costs, relating to farmers' perceptions, has been accentuated in several CEAP studies. The results of PA CEAP (Armstrong *et al.*, 2012) study of intermittent and ephemeral streams suggest that landowners with more regularly flowing streams were more concerned about stream water quality. IN CEAP study, Reimer *et al.* (2012b) investigated the relationship between farmers' perceptions about BMPs characteristics and adoption, with a focus on four BMPs (cover crops, conservation tillage, grassed waterways, and filter strips). The perceived relative economic and other personal advantage, compatibility with existing farming practices, and observability of either practice or its results were found to be most important in increasing the adoption of the BMPs in the study watershed.

The UT CEAP (Jackson-Smith and McEvoy, 2011) investigation of lasting impacts of different extension approaches underscored the long-term nature of both farmers' learning about water quality problems and the BMP adoption process in general. While the time dimension of the water quality modeling has been recognized widely (Tomer and Locke, 2011), the changing magnitudes of BMP costs due to improved knowledge about the practices and environmental awareness have not been considered explicitly in the CEA analyses, and are yet to be incorporated in future modeling.

BMP Placement Assessments

Three projects, NY CEAP (Rao *et al.*, 2012), KS CEAP (Langemeier *et al.*, 2010), and AR CEAP (Rodriguez *et al.*, 2011a) conducted the BCAs for 7, 6, and 10 scenarios, respectively. The water quality effects were modeled using the Variable Source Loading Function model (Schneiderman *et al.*, 2007) in the NY CEAP, and the Soil and Water Assessment Tool model (SWAT) (Arnold *et al.*, 1998; Arnold and Fohrer, 2005) in the KS CEAP and the AR CEAP BCAs.

Four projects carried out CEAs. IN CEAP (Oliver, 2008) conducted a CEA using the additively separable water quality functions derived from the BMP effectiveness estimates reported in various sources. ID CEAP (Tosakana *et al.*, 2007) used the Water Erosion Prediction Project model (Flanagan and Nearing, 1995; Flanagan *et al.*, 2007) for a CEA by applying a "brute force" approach of evaluating all possible combinations of placements of four BMPs on a relatively small number of land tracts in a watershed. The AR CEAP (Rodriguez *et al.*, 2011b) and IA CEAP (Rabotyagov *et al.*, 2010a, b) used the EAs in combination with SWAT to derive the functional relationships between the total costs and total benefits of cost-effective BMP placements.

The first important finding is that evolutionary algorithms provide feasible means for identifying cost-effective policies. The OR CEAP (Whittaker *et al.*, 2009) suggested a novel hybrid genetic algorithm for derivation of the functional relationships between the total costs and total water quality improvements of cost-effective BMP placements. The empirical assessments of the AR CEAP and IA CEAP showed that solving for cost-effective BMP placement in a reasonable amount of time is indeed possible even with a large number of BMPs and in a watershed divided into a realistically large number of sites. Rodriguez *et al.* (2011b) applied the EAs for identification of the cost-effective placements of 35 BMPs on a total of 461 sites to study the tradeoffs amongst the two competing objectives, the maximum water quality benefit, and the minimum cost of achieving it. The Rabotyagov *et al.* (2010a, b) studies applied the EAs for the cases of 32 BMPs with the total number of tracts as high as 1,312 to derive several functional relationships between the total costs and total benefits of cost-effective BMP placements.

A second finding is that the tradeoffs between total conservation program costs and optimal water quality improvements achieved through targeted BMP placements could be large, with the marginal abatement costs growing sharply with more stringent water quality goals. For example, Rabotyagov *et al.* (2010b) estimated the marginal abatement costs that could be interpreted as the cost of an additional water pollution reduction brought about by a conservation program, provided the BMPs are placed cost-effectively. Under 2005 land-use conditions, these costs were estimated to increase from $0.5 per kg of N for a 10% nitrate reduction goal to $4.2 per kg of N for a 30% nitrate reduction goal to $42.7 per kg of N for a 50% nitrate reduction goal for the study watershed. The study also found that as the nutrient reduction targets increase the optimal BMP mix shifts from mulch-till to suites that include no-till, grassed waterways, and terraces. These results have important implications for conservation policy design and implementation, suggesting that the sets of BMPs that are optimal under a given level of program funding may no longer be optimal under alternative levels of program funding. It remains to be verified in future research whether similar dependency of optimal set of BMPs on conservation program budget could be identified for other watersheds.

A third finding is that careful identification of the appropriate baseline for a BCA or a CEA is necessary. The implicit assumption in the CEA setup is that in considering the problem of placement of new BMPs, the conservation planner knows exactly the baseline, that is, current land use that includes the BMPs that have already been installed. Several CEAP projects pointed to significant difficulties that may be encountered while determining the baseline. As with BMP costs, the projects that relied on long-term effective connections to the local farming and conservation community had less difficulty acquiring the needed baseline data. The UT CEAP (Jackson-Smith *et al.*, 2010) showed that formal USDA NRCS records could be subject to errors concerning the incidence, timing, and/or location of BMP implementation. The study also found the probability of maintenance of structural practices was greater than that of management practices in the study watershed.

The IA CEAP (Rabotyagov *et al.*, 2010b) pointed to the importance of identifying the baseline for the CEA by explicitly comparing the CEA outcomes under two land-use conditions: one corresponding to the 2005 snapshot of the study watershed, and the other — predicted under the futures crop prices that favor corn over soy and are expected to draw more marginal land from land retirement into intensive crop production. The impact of the alternative baseline was shown to be dramatic, as demonstrated by the changes in the shapes and the ranges of the estimated functional relationships between the total costs and total benefits of cost-effective BMP placements, total minimum costs of achieving nutrient reductions, and in the suites of BMPs that make up cost-effective placements.

A fourth important finding is that water quality and economic uncertainties alter the cost-effective BMP placements considerably and need to be explicitly considered. With a growing theoretical literature on economic risk and water quality protection in agriculture (see, e.g., Bosch and Pease, 2000), more empirical assessments are needed. Several CEAP studies contributed to closing this gap. The BCA conducted by the AR CEAP (Rodriguez *et al.*, 2011a) found that ranking of BMP scenarios differed considerably if the standard metrics of scenario evaluation, total net returns (profits from production), and total reduction in phosphorus losses are supplemented with the measures of net return risks, where the risks originate from the impacts of the uncertain weather on Bermuda grass yields. The results of the study suggest that adding BMPs such as buffer zone and poultry litter applications to the current farming practices could increase the variability in net returns. As most economic agents prefer certain economic outcomes to uncertain ones, the findings of Rodriguez *et al.* (2011a) imply that traditional, explicit measures of costs may not capture the full opportunity costs of adopting BMPs, and the implicit costs related to risk aversion may be important in solving for cost-effective BMP placements.

A different aspect of uncertainty was the focus of the IA CEAP (Rabotyagov *et al.*, 2010a) that evaluated the tradeoffs between achieving cost-effective water quality improvements as measured using two alternative water quality metrics. In one case, the water quality improvement targets were set in terms of the mean annual nitrogen loadings, while in the other case it was assumed that specified nitrogen loadings targets must be met under every potential weather realization. The study found the total cost of achieving weather-resilient solutions to be significantly greater, with the additional total cost increasing with the water quality improvement target. Similar to Rodriguez *et al.* (2011a), Rabotyagov *et al.* (2010a) pointed to a broader need for development of robust cost-effective policies that account for the inherently uncertain nature of the BMP effectiveness for controlling agricultural pollution.

CONCLUSIONS

Both conservation practitioners and water resource and economics literature continue emphasizing the need to design policies to address agricultural nonpoint source water pollution in a cost-effective way. The present synthesis of the cross-cutting findings of the CEAP projects focused on two important aspects of such policy making, evaluation of BMP implementation costs, and the identification of watershed-scale cost-effective placements of BMPs. The CEAs conducted showed significant tradeoffs between the total conservation program costs and water quality improvements achieved through optimal BMP placements. Evolutionary algorithms have demonstrated workable ways to identify cost-effective BMP placements even for large, diverse watersheds, and large numbers of potential BMPs. This computational capacity opens up possibilities for conducting various previously unquantifiable assessments such as whether changes in the level of a conservation budget significantly affect which sets of practices would be most cost-effective and/or which geographic regions within the watershed are to be enrolled in the optimally designed program.

The collective experience of CEAP projects suggests that while close contacts with farmers and local conservation specialists greatly facilitate the acquisition of land use, farming practices, and cost information, in general, data availability remains a significant limiting factor for capturing the within-watershed variability in BMP costs and for finding cost-effective BMP placements. A potential solution to this challenge may lay in encouraging the practice of detailing the BMP cost components explicitly in the literature or by other means. The detailed documentation would assist in transferability of existing BMP cost estimates to alternative geographic regions such as those that have different labor or land costs, and the adaptability of the estimates to alternative economic conditions such as changing energy or crop prices.

Another notable finding underscored by the collective experience of the CEAP projects is that both explicit and implicit costs matter. With the large and growing literature that identifies social, cultural, and logistical barriers to the adoption of BMPs, a crucial, yet unanswered, research question remains on how to consistently integrate the probabilistic functional relationships that describe the impact of farm and farmer characteristics on implicit costs with the models that conventionally evaluate the explicit costs in dollar terms.

The importance of developing reliable BMP cost estimates that capture the full heterogeneity in economic, human, and natural conditions extends well beyond the simplest form of the voluntary BMP payment policy considered in this article. Cost information is of crucial importance for the more elaborate policies exemplified by the Environmental Quality Incentives Program and the Conservation Security Program (Horan and Claassen, 2007). Furthermore, as Horan and Shortle (2011) demonstrated, regulators cannot construct cost-minimizing markets for water quality without knowing individual producers' pollution abatement costs. Thus, the effectiveness of both voluntary and regulation-driven water quality policies would benefit from improved understanding of BMP costs.

APPENDIX: BRIEF SUMMARIES OF CEAP ECONOMICS STUDIES

Throughout the appendix, P denotes the number of BMPs and S denotes the number of land tracts considered in the corresponding BCA or CEA.

NY CEAP (Rao *et al.*, 2012) developed multiple year cost estimates for the net present value analysis of seven alternative BMP implementation scenarios in the watershed. Multiple components of the costs for two practices ($P = 2$), barnyard improvements and riparian buffers, including installation, maintenance, and the loss in income due to land taken out of production, were evaluated. A one-farm study watershed was subdivided into $S = 68$ land tracts that differ in current land use and/or wetness indices, but analysis was restricted to a smaller number of units as those representing deciduous forest, water, and rural roads were excluded.

KS CEAP (Langemeier *et al.*, 2010) quantified economic and water quality outcomes of six crop rotations under varying tillage intensity (conventional, reduced, or no-till) for an 18-year simulation and used the yearly average net return as a measure of relative profitability of one cropping system *vs.* another. The analysis was carried out for one, most common soil in the watershed, that is, $P = 3$ and $S = 1$ in this study.

IN CEAP economics studies are documented in Oliver (2008), Prokopy *et al.* (2008), and Reimer *et al.* (2012a, b). Oliver (2008) used cost estimates from various publications for $P = 10$ common BMPs (cropland protection, conservation tillage, contour farming, conversion to forest, conversion to wetland, nutrient management, terraces and diversions, vegetative buffers, waste management, runoff control) and the set of $S = 24$ farm and concentrated animal feeding operations to solve the cost-effectiveness problem for 5 alternatively defined metrics of water quality representing the concentrations of atrazine, N, P, sediment, and *Escherichia coli*. A water quality constraint was set up as a soft constraint to model potential penalties and rewards when pollutant concentration was lowered less and more than required by the constraint, respectively. The water quality function is additive across the sites, and is loosely associated with the study watershed. The tradeoffs between the various levels of the water quality target and the minimum cost of achieving the target were evaluated.

Prokopy *et al.* (2008) synthesized 55 studies on the determinants of BMP adoption in the U.S. conducted from 1982 to 2007. The study analyzed the impact of various measures of farmer capacity, attitude, and environmental awareness, as well as farm characteristics on the observed adoption of BMPs. The paper finds that farmer and farm characteristics such as education levels, capital, income, farm size, access to information, positive environmental attitudes, environmental awareness, and utilization of social networks impact the probability of adopting BMPs more often positively, rather than negatively, suggesting that the costs of BMP adoption may be lower for farms and farmers of the listed characteristics.

Reimer *et al.* (2012a) conducted 32 in-depth, semi-structured interviews with agricultural producers in the study watershed to investigate the relationships between multiple dimensions of environmental attitudes (farm as business, off-farm environmental benefits, and stewardship) and the adoption of four BMPs (conservation tillage, cover crops, grassed waterways, and filter strips). The study found that time and direct monetary constraints were commonly important factors deterring the adoption of the BMPs.

Reimer *et al.* (2012b) used in-depth interviews of 45 producers in the study watershed to elicit how their perceptions about the characteristics of four BMPs (conservation tillage, cover crops, grassed waterways, and filter strips) affect the adoption. The study finds that perceived relative advantage (or disadvantage) (financial and otherwise) and compatibility (or incompatibility) with existing farming practices are important for adoption (or non-adoption) of all BMPs considered. The ability to observe the practice and/or its impacts on water quality also increases the adoption of the BMPs. Perceived risk and complexity were found to be important in limiting the adoption of conservation tillage only.

The MO CEAP (Intarapapong *et al.*, 2008) evaluated the economic outcomes of a single BMP, grassed waterways, by comparing a watershed's representative farm's net returns with and without grassed waterways. The representative farm was developed based on the area-average farm physical characteristics (cropland area, crop rotations, tillage, and fertilizer and pesticide applications) and socioeconomic data obtained from a sample of 18 operators that agreed to participate in the survey. The costs of the BMP were broken down into establishment, maintenance, and the loss of income due to the land taken out of production ($P = 1$ and $S = 1$ in this study).

Economic findings from the AR CEAP are documented in Rodriguez *et al.* (2011a, b). Rodriguez *et al.* (2011a) conducted a BCA for 10 scenarios that differ in the use of suites of BMPs by Bermuda grass producers. Optimal grazing and a buffer were part of each suite, with the scenarios differing by poultry litter application rates, timing, and litter characteristics. The costs of each scenario were computed using budget analysis. The analysis was carried out for $S = 69$ subbasins within the study watershed. The analysis quantified the impact of the BMPs on not just expected net returns and phosphorus losses, but also on the variability of those stemming from the uncertainty about future weather. The goal of the watershed analysis was to identify the scenario that had greater total phosphorus reduction with less variability in NR when compared to baseline. The study found, among other things, that adding BMPs to current Bermuda grass production systems could lead to increased net returns variability.

Rodriguez *et al.* (2011b) conducted a CEA for $P = 35$ BMPs that vary in pasture management, buffer zones, and poultry litter application practices. A total of $S = 461$ pasture areas were considered for implementation of the BMPs. Cost data were derived from multiple sources, including the NRCS conservation practice manuals; the estimates explicitly accounted for the loss in yield due to pasture area reduction. The study used a nondominated sorting generic algorithm to develop multiple cost-effective allocations of BMPs, and to evaluate the tradeoff between the total cost and the decrease in total phosphorus as well as that between the total cost and the decrease in total nitrogen.

In the UT CEAP, Jackson-Smith and McEvoy (2011) evaluated the long-term effects of extension activities on farmers' decisions to participate in conservation activities. They found that the chances of participation in the program increased with previous relationships between farmers and program staff and one-on-one visits with landowners, while the impacts of demonstration projects and peer-to-peer social diffusion processes were found to be of less importance.

In the GA CEAP, the costs of terraces and grassed waterways were developed, and these were subsequently used by Jang *et al.* (2013). The cost estimates were attained in close collaboration with the local NRCS District Conservationist.

In the OR CEAP, Whittaker *et al.* (2009) developed a hybrid genetic algorithm for derivation of a Pareto optimal set. The new method was illustrated in an application that uses field experimental data to calculate the Pareto optimal set depicting the tradeoffs between the maximum nitrogen runoff reduction and the minimum reduction in profit because of a tax imposed on fertilizer use.

Tosakana *et al.* (2010, 2007) document ID CEAP economics results. The former study used a survey of 1,500 farmers to investigate what farm and farmer characteristics affect the adoption of BMPs and how important the perceived costs are for adoption of gully plugs and buffer strips. Tosakana *et al.* (2010) found that perceived effectiveness of the practice was positively associated with the adoption. The adoption of gully plugs was found to be positively affected by the size of the farm, and negatively by the proportion of leased land. They also found that the components of the explicit BMP costs were not perceived to be equally important by the farmers: installation costs were not viewed as important by the farmers as the maintenance costs in the study region.

Tosakana *et al.* (2007) developed detailed cost-of-production budgets through personal interviews for four farmers in the watershed to investigate the cost-effectiveness of $P = 4$ BMPs, gully plugs and buffer strips, each paired with mulch tillage or no-till. In the analysis, the fields of the farmers were subdivided into smaller tracts of land based on hillslopes and current farming practices. The CEA problem was solved for varying levels of desired reduction in sediment load.

In the PA CEAP, Brooks *et al.* (2011) and Armstrong *et al.* (2012) reported on landowners' perceptions and attitudes toward water quality problems and the ways to address the problems. Brooks *et al.* (2011) analyzed the results of a survey of riparian landowners to explore the factors that affect the adoption of riparian buffers. The buffers' perceived unsightly appearance, and significant land and time commitments were identified as obstacles to buffer adoption. The perceived improved understanding of stream water quality was associated with a greater willingness to adopt riparian buffers.

Armstrong *et al.* (2012) examined the relationship between streamflow regularity and riparian landowners' perceptions and attitudes toward water quality problems. The study found that landowners with intermittent and ephemeral streams are less likely to manage their properties for riparian or stream protection than those with regularly flowing streams.

Rabotyagov *et al.* (2010a, b) and Kling (2011) reported on IA CEAP economics results. Kling (2011) explored the potential use of observable proxies to support implementation of cost-effective policies in the case when the emissions from the fields and effectiveness of BMPs are not directly observable. A case study used evolutionary algorithms to construct Pareto frontiers for a non-CEAP watershed.

Rabotyagov *et al.* (2010a) considered two versions of the nitrogen reduction target in the CEA problem, one weather-resilient, that is, that to be met under every weather realization, and the other — to be met on average. Some $P = 32$ BMP suites that included alternative conservation tillage systems, contour farming, grassed waterways, terraces, reduction in nitrogen fertilizer applications, and land retirement were considered for a total of $S = 1{,}312$ land tracts. The study used evolutionary algorithms to identify cost-effective allocations of BMPs for specific water quality targets, and to evaluate the tradeoff between the total cost and mean nitrogen loading reductions as well as that between the total cost and nitrogen loadings reductions met in all of the 20 simulated weather years.

Rabotyagov *et al.* (2010b) considered two metrics of water quality in the CEA problem, total phosphorus loading and nitrate-nitrogen loading, and investigated how the corresponding Pareto optimal frontiers changed with changing crop prices. Two land-use scenarios were considered: current conditions, and future conditions for crop prices that favor corn over soy and are expected to draw more marginal land into production. The same set of P = 32 BMP suites as in Rabotyagov *et al.* (2010a) was considered, and the number of land tracts was S = 1,213 for the baseline scenario, and S = 1,206 for the alternative land-use scenario. The study found that the Pareto frontiers change with the land-use baseline. Moreover, the mix of cost-effective BMPs depended significantly on land use.

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