Penalties, Targeting, and Performance in Payment for Ecosystem Services Programs

Youngho Kim
youngk@umd.edu

Erik Lichtenberg
elichten@umd.edu

David A. Newburn
dnewburn@umd.edu

Department of Agricultural and Resource Economics
University of Maryland at College Park

Abstract. Studies of efficient selection of heterogeneous projects in payments for ecosystem services (PES) programs often recommend ranking those projects based on benefit-cost ratio criteria to maximize net environmental benefits. These analyses assume perfect completion of the selected project contracts, even though projects are conducted under long-term contracts that are sometimes terminated before their expiration dates. This paper proposes a theoretical model for adjusting benefit-cost ratio criteria to account for the possibility of premature termination of funded projects and investigates how that adjustment affects project rankings. A numerical policy simulation using features of the Conservation Reserve Enhance Program in the United States shows that project selection using the modified benefit-to-cost ratios reduces rates of contract early termination and increases net environmental benefits. These improvements generally become more substantial with greater program budgets and optimized structure of penalties for early termination. Our analysis indicates that refining project selection criteria to account for implementation frictions can improve performance of PES programs globally.

Keywords: payments for ecosystem services, agri-environmental programs, non-compliance penalty, targeting, contract design

JEL Codes: Q15, Q28, Q57, Q58

Selected Paper prepared for presentation at the 2023 Agricultural & Applied Economics Association Annual Meeting, Washington DC; July 23-25, 2023

1. INTRODUCTION

There is a substantial body of literature devoted to the efficient selection of projects for obtaining ecosystem services such as improvements in water quality, preservation of wildlife habitat, protection of endangered species, or carbon sequestration when spending is constrained in some way. A consistent finding of this literature is that projects should be ranked according to their ratios of benefits to costs and then selected in descending order until the relevant constraint binds. This selection rule has been shown to be robust to complicating factors such as the presence of multiple competing environmental goals (Babcock et al. 1996, Wu et al. 2001) and nonlinearities in environmental benefits due to interactions in nonpoint source pollutant emissions (Rabotyagov et al. 2014, Lang et al. 2020, Hansen et al. 2021). It is equally applicable to cost-effectiveness analyses, i.e., when benefits are measured in terms of quantities rather than money.[1]

These analyses derive the benefit-cost ratio selection rule for static situations with perfect compliance. In actuality, the programs that pay for ecosystem services typically do so under long term contracts into which landowners or farmers enter voluntarily. Well known examples from the United States include the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP), which pay landowners to convert highly erodible cropland into conservation uses like grassland or forest for periods of 10 to 15 years and the Environmental Quality Incentives Program (EQIP), which subsidizes the installation of crop and livestock structures and equipment used to reduce nutrient runoff and erosion under contracts that last 5 to 10 years. Long term contracts are desirable in such programs both as a means of assuring a continuing supply of environmental services and because the supply of those services typically

---

[1] The introduction of a similar project ranking process—use of a weighted average of environmental benefits and costs called the Environmental Benefits Index (EBI)—has been estimated to have increased performance of the CRP by roughly 25% (Feather et al. 1999).

increases over time due to vegetation growth, gradual improvements in soils, and similar factors (Engel 2015). However, it is by no means guaranteed that those who sign contracts will see those contracts through to completion, despite the fact that those signing contracts are obligated to repay all monies received should they withdraw from their contracts before the end of the contract lifetime. For example, Cattaneo (2003) found that 6% of farmers signing EQIP contracts signed during the 1997-2000 period withdrew from those contracts prematurely while an additional 17% dropped one or more of the conservation practices specified in their contracts before the end of the contract period. As many as 7-9% of CREP contracts for riparian buffers were terminated before the expiration dates of those contracts (Kim et al. 2022).

This paper focuses on one form of contract non-compliance, termination of contracts before their expiration dates. It examines how the prospect of premature contract termination should be taken into account in selecting projects for inclusion in voluntary payment for ecosystem services (PES) programs like CRP and CREP. We show theoretically how benefit-cost ratios should be modified to incorporate the possibility of premature contract termination. We use that theoretical model to investigate the factors that determine how incorporation of premature contract termination probabilities alters benefit-cost ratio project rankings. We extend the analysis of Kim et al. (2022), who derive a penalty structure that maximizes program performance in light of the possibility of premature termination for a single agent, to encompass contracts for multiple projects offered by heterogeneous agents. We then perform numerical simulation analysis using contract features of CREP to investigate the magnitude of improvements in PES program performance when incorporating the possibility of premature contract termination into project selection criteria. Preliminary results from Maryland indicate that total environmental benefits obtained net of program costs from the PES contracts can increase by as much as 10%. Additionally, relative improvements in program performance are increasing in program size. Since the current study region is relatively homogeneous, these results likely constitute a low-end estimate of potential improvements in program performance.

Our paper extends the existing literature on project selection in PES programs, specifically in cases where long-term contracts may be subject to non-completion. That literature dates back to empirical studies of the initial CRP signups of the late 1980s, which used numerical models to argue that those signups were consistent with maximizing acreage rather than erosion reduction (Reichelderfer and Boggess 1988) and that substantially greater environmental benefits were obtainable at the same level of spending (Ribaudo 1989). Babcock et al. (1996) showed formally that maximizing environmental benefits from discrete projects subject to a budget constraint generated a selection rule in which projects should be chosen in descending order of their benefit-cost ratios. They used that rule to investigate how weights placed on different environmental objectives affected the geographic distribution of CRP projects. Wu et al. (2001) extended the analysis of Babcock et al. to compare selection rules based on minimizing cost alone and maximizing environmental benefits alone with maximizing net benefits, with and without slippage. They used a numerical model to compare geographic concentration of CRP signups when different environmental benefits were used for targeting. A series of studies examining net benefit maximizing and cost-minimizing selection of projects featuring landscape changes (e.g., installation of streamside buffers) and installation of runoff-reducing farming practices to reduce nutrient loadings into water bodies finds that ranking parcels for selection using appropriately weighted benefit-cost ratios works well when water quality is affected by interactions between nonpoint source emissions from multiple locations (Rabotyagov et al. 2014, Lang et al. 2020, Hansen et al. 2021).

We proceed as follows. Section 2 presents a theoretical analysis of how a principal with a limited budget should offer PES contracts to a population of heterogenous agents in order to maximize environmental benefits net of the opportunity costs of foregone agricultural production when there is a possibility that agents may choose to withdraw from those contracts before those contracts' expiration date in response to changes in expectations of profit from alternative land uses or costs of maintaining contracted land-use practices. The optimal selection of projects has two components: (i) an optimal contract (upfront payment, a series of annual payments, and penalties for non-completion) to be offered to each landowner and (ii) selection of parcels to target for participation. We use the theoretical model to investigate the ways in which incorporation of premature termination possibilities affects project rankings. Section 3 presents a numerical policy simulation to investigate the magnitudes of differences in PES program performance. We base the numerical analysis on features of CREP to incentivize forest and grass riparian buffer adoption to meet water quality standards. Preliminary results indicate that incorporating the prospect of premature termination into project selection generates economically significant improvements in program performance, especially when penalties for early termination are structured optimally.

2. THEORETICAL FRAMEWORK

This section presents a theoretical analysis of a principal's optimal selection among projects offered by agents for providing ecosystem services over multiple time periods, along with optimal design of contract terms for those projects in cases where agents may find it in their interest to withdraw from contracts before the termination dates of those contracts. We use the theoretical framework to investigate qualitatively how project rankings that incorporate the possibility of premature contract termination differ from project rankings that ignore that possibility, as has been standard in the literature.

2.1 Model Setup

A principal (e.g., a government agency like the USDA or an NGO) runs a conservation program that offers long-term contracts for providing ecosystem services over a period of $t = 1, \ldots T$ years. There are $n = 1, \ldots, N$ agents (e.g., farmland owners) who can provide those projects. The opportunity cost of providing those services (which we model as foregone crop revenue) in each contract year is v_{nt} $(0 \leq t \leq T-1)$. Contract acceptance and thus the provision of ecosystem services is voluntary. The agent chooses to participate in the PES program initially if the present value of expected program returns under the contract exceeds the opportunity cost of participation over the contract lifetime, $\sum_{t=0}^{T-1} \delta^t v_{nt}$, where δ is a discount factor. Upon accepting the PES contract, the agent is obligated to generate ecosystem services from the contracted land-use practice at an installation cost k_n which is subsidized by the principal at a cost-share rate s. The contract specifies payments to the agent consisting of an upfront payment a_n and a series of annual payments r_n whose value is determined at the time of contract signing and remains fixed during the lifetime of the contract. If the agent terminates the contract before the expiration date, the contract specifies that the agent pays a penalty for contract non-completion at time t, p_{nt} in addition to incurring a conversion cost to remove the conservation land-use practice. That conversion cost, c_{nt}, may vary over time. The contract termination decision is irreversible and observable to the principal at a negligible monitoring cost that is fixed *ex ante*. The principal and all agents are assumed to be risk neutral.[2]

The agent maintains the measures that provide the contracted ecosystems services as long as the contract remains in force. The agent may, however, decide to withdraw from the contract if the opportunity cost increases sufficiently in any contract period. For example, a cropland owner participating in the CRP or CREP may decide to opt out of the program before the contract expiration date if a crop price shock leads the landowner to believe that the returns to reverting the land enrolled in the program to cropland (net of penalties and conversion costs) exceed the returns from keeping the land in the program. To capture this dynamic in a tractable way, we assume that the expected opportunity cost over the remaining contract periods at each time t is subject to an proportional random shock ε_{nt} $(0 < \varepsilon_{nt} \leq \varepsilon_{max})$ and is thus $\varepsilon_{nt} \sum_{t}^{T-1} \delta^{t} v_{nt}$. For tractability, we assume that ε_{nt} is i.i.d. with density of $f(\varepsilon_{nt})$, mean 1, and variance σ^2. This assumption implies that the *relative* magnitude of variability in total expected crop returns for the remaining contract periods is constant while the *absolute* magnitude of variability in those decreases during the contract lifetime.

We also assume that, at time 0, the opportunity costs of providing ecosystem services, the distribution of random shocks affecting those opportunity costs, the costs of installing measures that generate ecosystem services, and the conversion cost are the common knowledge of the principal and all agents. These are reasonable assumptions for agri-environmental programs like CRP and CREP. Farmers have a great deal of information about their operations, especially in light of the proliferation of precision agriculture tools and information about crop prices from USDA reports and futures market transactions. USDA agencies have at their disposal readily

---

[2] The analysis is easily extended to encompass risk averse agents by converting the expected opportunity costs to certainty equivalents.

accessible databases containing detailed information about soils (e.g., SSURGO), cropping patterns (e.g., CroplandCROS and the Cropland Data Layer), crop productivity (e.g., NCCPI), crop prices, average crop yields, average cropland rental rates, and average crop production costs (e.g., crop budgets produced at the state and federal levels). Finally, each project generates a stream of environmental benefits, B_{nt}, that varies across both agents and time. We assume that these benefits (or at least the expectations thereof) are known with certainty.

2.2. Two-Period PES Contracts

We begin with a two-period analysis of the principal's PES contract design and selection of PES projects in order to fix intuition. We then generalize the model to an arbitrary number of contract periods. The timing of actions is as follows. In the initial period, the principal offers a contract consisting of an upfront payment, a fixed annual payment, an installation cost-share, and a penalty for terminating the contract prior to the completion date. Also in the initial period, the agent chooses whether to accept the contract; if she does, she installs and maintains the conservation measure that provide the agreed-on ecosystem services (e.g., by converting cropland to grass or forest or by installing conservation practices) and receives a combination of the reimbursement for a fixed portion of any installation costs, an upfront payment, and the first annual payment.

A random shock affecting the next period's opportunity cost ε_1 occurs before the start of that next period. If the shock increases the opportunity cost of participating in the program sufficiently, $v_{n1}\varepsilon_1 > r_n + p_{n1} + c_{n1}$, the agent withdraws from the contract before the start of the next period, foregoing the second annual payment r_n and incurring the penalty specified in the contract p_{n1} along with any costs of converting her operation back to more productive use c_{n1}. The *ex-ante* probability of contract completion in the two-period case is thus:

$$Pr(v_{n1}\varepsilon_1 - p_{n1} - c_{n1} \leq r_n) = Pr\left(\varepsilon_1 \leq \frac{r_n + p_{n1} + c_{n1}}{v_{n1}} \equiv L_n\right) = \int_0^{L_n} f(\varepsilon_1)d\,\varepsilon_1 = F(L_n). \quad (1)$$

Note that the probability of premature contract termination differs for each agent n. Note also that the penalty p_{n1} directly increases the *ex-ante* likelihood of contract completion by increasing the minimum level of random shock ε_1 that triggers contract termination at time 1, L_n. Figure 1 illustrates the timeline of these decisions.

The agent is offered a contract at time 0 and accepts that contract if it offers an expected present value of returns that exceeds the expected present value of the opportunity cost of providing the agreed-on ecosystem services. The agent's expected return in the second period equals the average of (a) the annual payment from the contract received at time 1, r_n, if remaining in compliance, and (b) net returns from withdrawing from the contract before it terminates, which equals the opportunity cost savings if the shock exceeds the critical level $E\{v_{n1}\varepsilon_1 | \varepsilon_1 \geq L_n\}$, less the sum of the early termination penalty and the conversion cost, $p_{n1} + c_{n1}$. The agent thus chooses to accept the contract at time 0 if:

$$a_n + r_n - (1-s)k_n + \delta r_n F(L_n) + \delta \int_{L_n}^{\varepsilon_{max}} (v_{n1}\varepsilon_1 - p_{n1} - c_{n1}) f(\varepsilon_1) d\varepsilon_1 \geq v_{n0} + \delta v_{n1}. \quad (2)$$

The principal chooses both (a) the contract terms to offer for each project and (b) which projects to offer contracts for a given budget constraint over the entire lifetime of the cohort of contracts chosen at time 0, Q_0. Contract terms for each of the $n = 1, \dots, N$ heterogeneous projects include an upfront payment a_n, a series of annual payments r_n, and a non-completion penalty p_{n1}. Each project generates a time path of environmental benefits $\{B_{n0}, B_{n1}\}$. The principal recognizes the possibility that the agent may withdraw from the contract prior to time 1 and adjusts her expectation of overall environmental benefits obtained accordingly.

The principal's objective is to choose (a) contract terms and (b) project offers to maximize expected environmental benefits net of contract costs subject to the constraints on (i) its overall budget and (ii) the fact that contract terms must be structured to induce acceptance (i.e., satisfy each agent's participation condition). The principal's decision problem is thus:

$$\max_{I_n, a_n, r_n, p_{n1}} \sum_n I_n \left\{B_{n0} + \delta B_{n1} F(L_n) - a_n - sk_n - r_n\left[1 + \delta F(L_n) + \delta p_{n1}[1 - F(L_n)]\right]\right\} \quad (3)$$

subject to all agents' participation conditions in equation (2) and an overall constraint on spending over the entire lifetime of the cohort of all contracts signed at time 0:

$$\sum_n I_n \{a_n + sk_n + r_n[1 + \delta F(L_n)] - \delta p_{n1}[1 - F(L_n)]\} \leq Q_0, \quad (4)$$

where $0 \leq I_n \leq 1$ takes on a value of 1 if agent n is offered a contract for the full project, a value between 0 and 1 if agent n is offered a contract for a portion of the project, and 0 if agent n is not offered a contract for the project. Assume that the principal adjusts payment terms offered to each agent $\{a_n, r_n\}$ so that the participation condition binds with equality. Substituting each agent's binding participation condition into both the principal's objective function in equation (3) and the budget constraint in equation (4) yields the concentrated Lagrangian:

$$\begin{aligned} \mathcal{L} = \sum_n I_n \left\{B_{n0} + \delta B_{n1} F(L_n) - \left[v_{n0} + \delta v_{n1} + k_n - \delta \int_{L_n}^{\varepsilon_{max}} (v_{n1}\varepsilon_1 - c_{n1}) f(\varepsilon_1) d\varepsilon_1\right]\right\} \quad (5) \\ + \lambda \left[Q_0 - \sum_n I_n \left\{v_{n0} + \delta v_{n1} + k_n - \delta \int_{L_n}^{\varepsilon_{max}} (v_{n1}\varepsilon_1 - c_{n1}) f(\varepsilon_1) d\varepsilon_1\right\}\right] \end{aligned}$$

2.3 Optimal Contract Offers

The optimal choice of whether to offer a contract to agent n is obtained by taking the derivative of the Lagrangian in equation (5) with respect to I_n. Rearranging this necessary condition yields a benefit-cost ratio criterion of the form:

$$\rho_n^* \equiv \frac{B_{n0} + \delta B_{n1} F(L_n)}{v_{n0} + \delta v_{n1} + k_n - \delta \int_{L_n}^{\varepsilon_{max}} (v_{n1}\varepsilon_1 - c_{n1}) f(\varepsilon_1) d\varepsilon_1} \geq 1 + \lambda^*. \tag{6}$$

As is standard in the literature, the principal's algorithm for choosing which agents to offer contracts is to rank parcels according to the ratio of expected environmental benefits to the expected costs, then offering contracts in descending order of benefit-cost ratios until the budget is exhausted. of enrollment.

The benefit-cost ratio ρ_n^* in equation (6) differs from the standard in the literature,

$$\rho_n^o \equiv \frac{B_{n0} + \delta B_{n1}}{v_{n0} + \delta v_{n1} + k_n} \geq 1 + \lambda^o, \tag{7}$$

in that ρ_n^* adjusts both expected environmental benefits and expected opportunity costs for the likelihood of premature contract termination. The ratio of the benefit-cost ratios in equations (6) and (7) is:

$$\frac{\rho_n^*}{\rho_n^o} = \frac{\dfrac{B_{n0} + \delta B_{n1} F(L_n)}{v_{n0} + \delta v_{n1}\left[1 - \int_{L_n}^{\varepsilon_{max}} \varepsilon_1 f(\varepsilon_1) d\varepsilon_1\right] + k_n + \delta c_{n1}[1 - F(L_n)]}}{\dfrac{B_{n0} + \delta B_{n1}}{v_{n0} + \delta v_{n1} + k_n}} \tag{8}$$

Rewriting terms and rearranging yields:

$$\frac{\rho_n^*}{\rho_n^o} = \frac{1 - \dfrac{\delta B_{n1}[1 - F(L_n)]}{B_{n0} + \delta B_{n1}}}{1 - \dfrac{\delta[v_{n1}E(\varepsilon_1|\varepsilon_1 L_n) - c_{n1}][1 - F(L_n)]}{v_{n0} + \delta v_{n1} + k_n}} > (<) 1 \tag{9}$$

$$as\ \frac{B_{n1}}{B_{n0} + \delta B_{n1}} < (>)\ \frac{v_{n1}E(\varepsilon_1|\varepsilon_1 \geq L_n) - c_{n1}}{v_{n0} + \delta v_{n1} + k_n}$$

The term on the left hand side of the second inequality is the percentage loss in environmental benefits due to early termination of the contract as a share of total expected benefits. The term on the right hand side of the inequality is the percentage reduction in opportunity cost due to early termination as a share of the total opportunity cost of obtaining full environmental benefits. If the percentage loss of benefits due to early termination for a given parcel is less than the percentage reduction in opportunity cost in that parcel, the standard benefit-cost ratio in the literature is lower than the benefit-cost ratio when the possibility of early termination is taken into account. Put another way, the standard procedure for ranking parcels overestimates the attractiveness of parcels for which environmental benefits are more sensitive to early termination than opportunity costs. Conversely, the standard procedure for ranking parcels underestimates the attractiveness of parcels for which opportunity costs are more sensitive to early termination than environmental benefits.

2.4 Optimal Contract Terms

As noted above, the principal sets the terms of an individualized contract to be offered to each agent such that the agent's participation constraint binds with equality. Along with the installation cost-share rate, the contract contains two types of terms: (1) a positive incentive consisting of a combination of upfront and annual payments and (2) a set of penalties to be imposed in the case of premature contract termination.

Positive incentive packages differ across US programs: CRP pays only annual payments determined by reverse auctions while CREP offers annual payments set by formula according to average rents in each county adjusted for soil productivity, augmented at times by signing bonuses. A single form of payment is sufficient for the purposes of our analysis. To simplify computations, we therefore assume that annual payments are fixed by formula and that the principal chooses upfront payments to meet each agent's participation constraint, an approach much like that taken by CREP. Under this assumption, the annual payment for each agent r_n is fixed and the upfront payment a_n is chosen to ensure that each agent's participation constraint binds:

$$a_n^* = v_{n0} + \delta v_{n1} - r_n + (1-s)k_n - \delta\left[F(L_n)r_n + \int_{L_n}^{\varepsilon_{max}} (v_{n1}\varepsilon_1 - p_{n1}^* - c_{n1})f(\varepsilon_1)d\,\varepsilon_1\right]. \quad (10)$$

Penalties are imposed on agents who terminate contracts before the end of the contract period. In such cases, every program in the United States—like most programs worldwide—requires agents to repay all monies received under the contract up to the premature termination date. In essence, the principal requires a money-back guarantee when an agent fails to remain bound by her contract. Formally, this standard penalty structure is

$$p_{n1}^0 = \frac{1}{\delta}(a_n^0 + sk_n + r_n). \quad (11)$$

As Kim et al. (2022) show, this standard approach is not optimal: By creating a direct coupling between payments and penalties, this standard penalty structure attenuates incentives for agents' participation incentives. As Kim et al. also show, the optimal penalty for each agent is:

$$p_{n1}^* = B_{n1} - r_n. \quad (12)$$

This optimal structure sets the penalty for premature termination equal to the net value of environmental benefits the principal fails to obtain. In other words, instead of a money-back guarantee, the optimal penalty requires agents to pay for the environmental benefits the principal would receive had the contract remained in force for the remainder of the contract period, net of the principal's cost of acquiring those environmental benefits. Since agents are heterogeneous in terms of potential environmental benefits as well as opportunity costs (and thus program payments), this optimal penalty will vary across agents.

It is straightforward to show that the optimal penalty structure is invariant with respect to the structure of incentive payments, i.e., the penalty structure given by equation (12) remains optimal when incentives consist only of annual payments chosen so that the participation constraint binds, as in the case of the CRP.

2.5. Generalization to Multi-period PES Contracts

We now extend our analysis in the two-period contract to a multi-period PES contract with arbitrary contract length T. We extend the derivation in Kim et al. (2022), who examine optimal contracts for a single representative agent, to encompass heterogeneous agents. The timing of actions remains essentially the same as in the two period case: After the initial period, a multiplicative random shock occurring before the start of each subsequent period alters the expected opportunity costs of providing ecosystem services for the remainder of the contract period. If the shock increases the opportunity cost of remaining in the program sufficiently, some agents will choose to opt out of their contracts before their contracts' expiration dates, paying a penalty and incurring conversion costs when they do so.

As in the two-period case, the probability that agent *n* remains in the PES contract is:

$$F_{nt} = Pr(\varepsilon_t \leq L_{nt}) = \int_0^{L_{nt}} f\,(\varepsilon_t)d\varepsilon_t, (1 \leq t \leq T-1). \tag{13}$$

The minimum size of random shock that triggers premature contract termination at time t, L_{nt}, is:

$$L_{nt} = \frac{M_{nt} + p_{nt} + c_{nt}}{\left(\sum_{j=t}^{T-1} \delta^{j-t}\, v_{nj}\right)}, \qquad 1 \leq t \leq T-1. \tag{14}$$

Here M_{nt} denotes the agent's expected returns time *t* until the end of the contract period *T*. The agent's expected returns of take into account the chance that she will remain in compliance with the PES contract in each future period along with the chance that she will decide to opt out of her contract in each future period:

$$M_{nt} = r + \delta\left\{F_{nt+1}M_{nt+1} + \int_{L_{nt+1}}^{\varepsilon_{max}}\left[\left(\sum_{j=t+1}^{T-1} \delta^{j-t+1}\, v_{nj}\right)\varepsilon_{t+1} - p_{nt+1} - c_{nt}\right] f(\varepsilon_{t+1})d\varepsilon_{t+1}\right\}. \tag{15}$$

Since the random shocks are assumed to be i.i.d., the *ex-ante* survival probability that an agent remains in the contract at time t is:

$$\prod_{j=1}^{t} F_{nj}\,. \tag{16}$$

The agent's participation condition in the multi-period case is:

$$a_n - (1-s)k_n + \left(\prod_{t=1}^{T-1} F_{nt}\right)\left(\sum_{t=0}^{T-1} \delta^t\, r_n\right) \tag{17}$$

$$+\sum_{j=0}^{T-2}\left\{\left(\prod_{t=0}^{j} F_{nt}\right)\int_{L_{nj+1}}^{\varepsilon_{max}}\left[\sum_{l=0}^{j} \delta^l\, r_n + \left(\sum_{q=j+1}^{T-1} \delta^q\, v_{nq}\right)\varepsilon_{j+1}\right.\right.$$

$$\left.\left. - \delta^{j+1}\left(p_{nj+1} + c_{nj+1}\right)\right] f\left(\varepsilon_{j+1}\right) d\varepsilon_{j+1}\right\} \geq \sum_{t=0}^{T-1} \delta^t\, v_{nt}.$$

As in the two-period case, the agent's expected return in each period consists of (a) annual payments received from the PES program and (b) all expected future income earned from converting her land back to productive use after withdrawing from the PES program, net of PES program penalties and conversion costs. Each of these two components is weighted by its respective probability.

Also as in the two-period case, the principal chooses both contract offers and contract terms for each agent $\{a_n, r_n, p_{n1}, \dots p_{n,T-1}\}$ in order to maximize environmental benefits less project payments:

$$max_{I_n, a_n, r_n, p_{n1}, p_{n2}, \dots, p_{n,T-1}} \sum\nolimits_n I_n \left\{-a_n - sk_n + \left(\prod_{t=1}^{T-1} F_{nt}\right)\left(\sum_{t=0}^{T-1} \delta^t (B_{nt} - r_n)\right)\right\} \tag{18}$$

$$+\sum\nolimits_n I_n \sum_{j=0}^{T-2}\left(\prod_{t=0}^{j} F_{nt}\right)\left(1 - F_{nj+1}\right)\left[\sum_{l=0}^{j} \delta^l (B_{nl} - r_n) + \delta^{j+1} p_{nj+1}\right]$$

subject to the agent's participation constraint above and the overall T-period budget constraint:

$$\sum\nolimits_{n} I_n \left\{ a_n + sk_n + \left(\prod_{t=1}^{T-1} F_{nt} \right) \left(\sum_{t=0}^{T-1} \delta^t r_n \right) + \sum_{j=0}^{T-2} \left(\prod_{t=0}^{j} F_{nt} \right) (1 - F_{nj+1}) \left[\sum_{l=0}^{j} \delta^l r_n - \delta^{j+1} p_{nj+1} \right] \right\} \leq Q_0 \quad (19)$$

This budget constraint embodies an assumption that the principal allocates a fixed sum to cover all expenses it expects to incur under all contracts signed for a single cohort of agents over the entire lifetime of those contracts. In essence, we treat the principal's budget for that cohort of contracts (e.g., a single CRP signup period) as if it were deposited in an escrow account bearing interest at the rate $\frac{1-\delta}{\delta}$. For government programs, this formulation of the budget constraint corresponds to an assumption that funds obligated at time zero cost the government less in the when expended in the future because of the real rate of growth of the economy, also treated as $\frac{1-\delta}{\delta}$. Note that this budget formulation also assumes that any penalties assessed are returned to the principal; for government programs, the equivalent is that any penalties assessed are returned to the same agency rather than going back into general funds. While this latter assumption may not be completely realistic, it does capture the fact that both payments and penalties are transfers from the principal to the agents and are thus not components of social welfare.

As in the two-period case (equation (6)), the principal ranks projects according to their benefit-cost ratios adjusted for early termination probabilities:

$$\rho_n^* \equiv \tag{20}$$

$$\frac{(\prod_{t=1}^{T-1} F_{nt})(\sum_{t=0}^{T-1} \delta^t B_{nt}) + \sum_{j=0}^{T-2} (\prod_{t=0}^{j} F_{nt})(1 - F_{nj+1}) \sum_{l=0}^{j} \delta^l B_{nl}}{k_n + \sum_{t=0}^{T-1} \delta^t v_{nt} - \sum_{j=0}^{T-2} \left\{ (\prod_{t=0}^{j} F_{nt}) \int_{L_{nj+1}}^{\varepsilon_{max}} [(\sum_{q=j+1}^{T-1} \delta^q v_{nq}) \varepsilon_{j+1} - \delta^{j+1} c_{nj+1}] f(\varepsilon_{nj+1}) d\varepsilon_{j+1} \right\}}$$

$$\geq 1 + \lambda^*.$$

The principal then selects agents to make offers to in descending order of their projects' benefit-cost ratios until its ability to fund projects runs out.

The standard benefit-cost ratio in the literature implicitly assumes perfect compliance with contract terms and thus does not adjust for the possibility of premature PES contract termination:

$$\rho_n^o \equiv \frac{\sum_{t=0}^{T-1} \delta^t B_{nt}}{k_n + \sum_{t=0}^{T-1} \delta^t v_{nt}} \geq 1 + \lambda^o \tag{21}$$

As in the two-period case in equation (8), the ranking of any project depends on the relative sensitivities of expected environmental benefits and expected opportunity costs to premature termination:

$$\frac{\rho_n^*}{\rho_n^o} = \frac{\dfrac{\sum_{j=0}^{T-2}\left(\prod_{t=0}^{j} F_{nt}\right)\left(1 - F_{nj+1}\right)\sum_{l=0}^{j} \delta^l B_{nl}}{\sum_{t=0}^{T-1} \delta^t B_{nt}}}{\dfrac{\sum_{j=0}^{T-2}\left\{\left(\prod_{t=0}^{j} F_{nt}\right)\int_{L_{nj+1}}^{\varepsilon_{max}}\left[\left(\sum_{q=j+1}^{T-1} \delta^q v_{nq}\right)\varepsilon_{j+1} - \delta^{j+1} c_{nj+1}\right] f\left(\varepsilon_{nj+1}\right) d\varepsilon_{j+1}\right\}}{k_n + \sum_{t=0}^{T-1} \delta^t v_{nt}}} \tag{22}$$

The numerator of this ratio is the expected percentage loss of environmental benefits from early termination at each year during the lifetime of the contract offered to agent *n*. The denominator is the percentage reduction in agent n’s opportunity cost of remaining in compliance with the terms of the contract. Lost environmental benefits and savings in opportunity costs in any given year are both weighted by the probability of early termination in that year, conditional on the contract having remained in force up until that year. As in the two-period case, the standard procedure for ranking projects overestimates the attractiveness of projects for which environmental benefits are more sensitive than opportunity costs to early termination and vice versa.

The terms of the contracts offered to each agent have the same structure as in the two-period case. As before, we follow the structure of CREP and treat annual payments as fixed by formula. The principal therefore adjusts the upfront payment for each agent to ensure that the agent’s participation constraint binds with equality:

$$a_n^* = \tag{23}$$

$$\sum_{t=0}^{T-1}\delta^{t}\,v_{nt}-\sum_{j=0}^{T-2}\left\{\left(\prod_{t=0}^{j}F_{nt}\right)\int_{L_{nj+1}}^{\varepsilon_{max}}\left[\sum_{l=0}^{j}\delta^{l}\,r_{n}+\left(\sum_{q=j+1}^{T-1}\delta^{q}\,v_{nq}\right)\varepsilon_{j+1}\right.\right.$$

$$\left.\left.-\,\delta^{j+1}\left(p_{nj+1}+c_{nj+1}\right)\right]f\left(\varepsilon_{j+1}\right)d\varepsilon_{j+1}\right\}+(1-s)k_{n}-\left(\prod_{t=1}^{T-1}F_{nt}\right)\left(\sum_{t=0}^{T-1}\delta^{t}\,r_{n}\right).$$

As Kim et al. (2022) show for a single agent, the optimal penalty for premature termination imposed on agent n during any period of the contract's lifetime is:

$$p_{nt}^{*}=\frac{1}{\delta^{t}}\left[\sum_{j=t}^{T-1}\delta^{j}\left(B_{nj}-r_{n}\right)\right],\quad 1\leq t\leq T-1. \tag{24}$$

The optimal penalty at time t equals the total foregone environmental benefits net of program costs for the remaining contract periods. As in the two-period case, the optimal penalty requires an agent who drops out of the signed contract prematurely to pay the monetary value of the environmental benefits that the principal would have received had the agent chosen to continue in the signed contract. That structure differs qualitatively from the standard penalty structure that requires reimbursement of all payments received commonly found in the existing PES programs:

$$p_{nt}^{0}=\frac{1}{\delta^{t}}\left[a_{n}^{0}+sk_{n}+\left(\sum_{j=0}^{t-1}\delta^{j}\,r_{n}\right)\right] \tag{25}$$

The standard penalty increases during the lifetime of the contract, as payments received increase each year that the agent remains in the contract. The optimal penalty, in contrast, decreases during the lifetime of the contract, as total future expected environmental benefits shrink along with the number of contract periods remaining. The time paths of the two penalty structures are thus diametric opposites: The optimal penalty starts at its highest value and declines during the lifetime of the contract while the standard penalty starts at its lowest value and increases during the lifetime of the contract.

3. NUMERICAL POLICY SIMULATION

We conduct a numerical policy simulation to explore the extent to which failing to account for the possibility of premature contract termination affects project rankings and thus PES program performance. We compare several dimensions of PES program performance under three scenarios: projects ranked according to the standard benefit-cost ratio that does not account for the possibility of premature termination (Scenario 1), projects ranked according to benefit-cost ratios adjusted for premature contract termination under the current standard penalty structure (Scenario 2), and projects ranked according to benefit-cost ratios adjusted for premature contract termination under the optimal penalty structure (Scenario 3). Agents' behavior and thus premature contract termination rates and environmental benefits attained are based on the penalty structures they face. Dimensions of program performance include net environmental benefits, the size of projects enrolled, and premature termination rates.

Our simulation is based on features of the CREP riparian buffer program. CREP is part of the larger CRP. The best known—and by far the largest—part of the CRP pays farmers to convert highly erodible land to conservation uses like grassland or forest under contracts lasting 10 to 15 years. This part of the CRP ranks parcels via an Environmental Benefits Index that combines an onsite assessment of environmental benefits by USDA technicians with rental rates bid by farmers. Signups are conducted on an annual basis using a competitive reverse auction. A smaller portion of the CRP signs 10-to-15 year contracts on a continuous basis for parcels on highly erodible land designated as especially sensitive, with payments determined by formula. In some locations, federal payments for specific conservation measures under the continuous signup CRP program are augmented by state funds. This latter program, CREP, is a federal-state partnership program that pays farmers to install and maintain conservation measures such as streamside vegetation (riparian buffers and filter strips), wetlands restoration, and wildlife habitat in locations designated as being of special environmental importance. Like all CRP contracts, CREP contract last from 10 to 15 years. Annual CREP payments are multiples of a soil rental rate that equals average county rental rates adjusted for soil productivity. Upfront payments include a Sign-up Incentive Payment and cost-sharing conservation practice installation. (Hellerstein (2017), Claassen et al. (2018), and Baylis et al. (2022) provide more complete discussions of these programs).

CREP has been used in the Mississippi River Basin to fund planting of streamside vegetation and restoration of wetlands in flood-prone locations. In the Pacific Northwest, CREP has funding tree planting to provide shade for salmon streams and fencing to keep livestock out of salmon streams. In the Chesapeake Bay region, CREP has been used to install riparian buffers to reduce nutrient and sediment runoff into the Bay. Maryland's CREP riparian buffer program plays a key role in plans to meet the EPA mandated Total Maximum Daily Load (TMDL) requirements for reducing agricultural nutrient and sediment loads into the Chesapeake Bay. The State's goal is to have grass or forest buffers installed on 70% of its streamside miles. The current statewide average is 60%, with shortfalls occurring most commonly in the heavily agricultural counties on the Eastern Shore of the Bay. Streamside mileage in Maryland increased rapidly between the end of the 1990s, when USDA approved increases in incentive payments for the State, and the early 2000s. Buffer mileage has expanded much more slowly since 2003. The State recently increased signing bonuses in an attempt to ramp up buffer installation.

The preliminary analysis reported here focuses on a single county on the Eastern Shore, Queen Anne's County. Queen Anne's County is the largest agricultural county in the State of Maryland. It specializes in corn, soybeans, and small grains grown in rotation and sold to local poultry integrators for feed formulation. It is also an important contributor of nonpoint source nutrient and sediment emissions into the Chesapeake Bay. Our numerical analysis focuses on water quality improvements attained via contracts to install and maintain grass buffers under 10-year CREP contracts on cropland in the county with surface water frontage.

3.1 Model Parameters

Parameters used in the numerical model include annual payments (determined by USDA's soil rental rate formula), opportunity costs of foregone crop income due to installation of buffers on cropland, the distribution of i.i.d. random shocks that affect those opportunity costs, buffer installation and removal costs, impacts of buffer installation on delivery of nitrogen, phosphorus, and sediment to the Bay, and the value of water quality improvements.

Spatially differentiated project identification. We combine information from the Maryland Department of Planning's spatially explicit complete parcel-level tax assessor database with USGS's National Hydrography Data to identify the locations of every parcel of land with both an agricultural use tax assessment and surface water frontage. We then select the subset of this set of parcels that has at least 10 acres of cropland according to the USDA's Cropland Data Layer so that our analysis encompasses all farmland in the county potentially eligible for riparian buffer installation under CREP, a total of 1288 parcels. We assume that all riparian buffers have a width of 100 feet. Potential riparian buffer acreage in each parcel is thus calculated by multiplying surface water frontage by 100 feet. We use the Soil Survey Geographic Database (SSRUGO) published by USDA's Natural Resource Conservation Service to identify the top three area dominant soil types within the 100-foot riparian zone of each parcel. We use USDA's National Commodity Crop Productivity Index (NCCPI) to estimate relative crop productivity within the

100-foot riparian zone. We use location-specific parameters from the Chesapeake Bay Watershed Model (CBWM) to estimate changes in nutrient and sediment deliveries to the Chesapeake Bay induced by installing riparian buffers on former cropland. Details of the calculations used are given below.

Program payments. We calculate annual CREP payments using the formula of USDA's Farm Service Agency (FSA). The annual CREP payment is set to a multiple of the buffer area's soil rental rate (SRR). The soil rental rate equals the county average cash rental rate for non-irrigation cropland reported by the National Agricultural Statistics Service (NASS), adjusted for relative crop productivity. The current annual payment is set at 2.5 times each parcel's SRR. CREP reimburses participants for half of the cost of installing vegetative buffers (i.e., the cost-share rate equals 50%). The upfront payment is set to the minimum needed to ensure that the participation constraint binds with equality.

Opportunity cost of land. The opportunity cost of installing riparian buffers on former cropland equals the expected crop return foregone during each year the contract period v_{nt}. We assume that the expected crop return is constant over time but can vary due to random shocks. We base the expected return to crop production on corn profitability (gross revenue less variable and annualized fixed costs for non-irrigated corn with conventional tillage), estimated by the University of Maryland's 2021 crop budget to be \$226/acre at the state level. We then adjust the state-level estimate to a Queen Anne's county equivalent by multiplying the state-level average of \$226 per acre by the ratio of the cash rental rate for non-irrigated cropland in Queen Anne's County to the state average cash rental rate for non-irrigated cropland. Finally, we adjust county-level estimate to a parcel-level estimate by multiplying the county-level average return per acre by the ratio of each parcel's NCCPI to the overall Queen Anne's County average NCCPI.

Distribution of random shocks to opportunity cost. Following Kim et al. (2022), we use the distribution of the error term from a logged autoregressive process to estimate the distribution of the i.i.d. multiplicative random shocks affecting the expected opportunity costs of land. The estimating equation is

$$ln\left(\frac{y_t}{y_{t-1}}\right) = \gamma + \beta_1 ln(y_{t-1}) + \beta_2 ln(y_{t-2}) + \cdots + \beta_h ln(y_{t-h}) + u_t, \tag{21}$$

where y_t is the landowner's crop return at time t and β_1, β_2, ..., β_h represent contribution of crop returns in the most recent lagged h years. We use the proportional deviation of y_t from its expectation, $exp(\hat{u}_t)$, as the i.i.d. random shock to expected future crop returns. We use annual gross crop revenue in Maryland as reported by NASS for the period 1951-2020. Four-year lags had the best fit. The distribution of the exponentiated residual $exp(\hat{u}_t) = \varepsilon_t$ is lognormal with mean 1.13 and standard deviation 0.25.

Riparian buffer installation and removal costs. Estimates of the cost of installing a grass buffer in Maryland average \$320 per acre in 2020 dollar terms (Price et al., 2021). We assume that the cost of removing a grass buffer equals half of the buffer installation cost, \$160 per acre, regardless of the age of the buffer.

Environmental benefits. Riparian buffers provide a wide variety of environmental amenities, including enhancements to terrestrial and aquatic wildlife habitat and carbon sequestration in addition to reductions of agricultural nonpoint source water pollution and stream bank erosion (Belt et al., 2014; Lee et al., 2003; Sweeney and Newbold, 2014). We restrict our attention to the latter, i.e., downstream water quality benefits. Installing buffers has both direct and indirect effects on water quality. The direct effects consist of reductions in nutrient and sediment loads from the land converted from cropland to vegetative buffer. This direct effect occurs at the time the buffer is installed and continues at the same level thereafter. The indirect effect consists of reductions in nutrient and sediment due to the buffer's filtering nutrient and sediment runoff from the adjacent remaining cropland before it reaches surface water. The indirect effect increases over time as the vegetation in the buffer matures.

We combine parameters from Chesapeake Bay Watershed Model (CBWM) with published estimates of nutrient and sediment removal rates to obtain spatially differentiated estimates of both the direct and indirect effects of riparian buffer installation on water quality. The direct effect for each parcel equals the difference in the CBWM delivery factors of cropland and grassland for each parcel. Indirect effects are estimated under the assumption that each acre of riparian buffer can filter and reduce nitrogen loads from four acres of adjacent cropland and phosphorus and sediment loads from two acres of adjacent cropland. CBWM parameters are used to estimate these pollutant loads. The shares of nitrogen, phosphorus, and sediment runoff removed by the buffer are assumed to increase over time as the grass cover matures. We use an exponential function with maximum removal rates of 0.46 for nitrogen, 0.42 for phosphorus, and 0.56 for sediment as estimated by Belt et al. (2014). We further assume that the initial removal rate equals half of its maximum rate. Further details of these calculations can be found in Appendix A of Kim et al. (2022).

Finally, we follow Choi et al. (2020) and set the monetary value of reductions in nutrient loadings into the Bay equal to $14.96 per pound for nitrogen, $181.61 per pound for phosphorus, and $0.37 per pound for sediment in year 2015 dollars, which we then adjusted to current dollars using the CPI.

Policy scenarios. As noted above, we compare outcomes under three scenarios: (1) projects ranked according to standard benefit-cost ratios that do not account for the possibility of premature termination (Scenario 1), (2) projects ranked according to benefit-cost ratios adjusted for premature contract termination under the current standard penalty structure (Scenario 2), and (3) projects ranked according to benefit-cost ratios adjusted for premature contract termination under the optimal penalty structure (Scenario 3). Upfront payments are adjusted such that each agent's participation constraint binds with equality. Agents who are offered a contract are thus assumed to participate in the program. Inframarginal agents, i.e., those whose benefit-cost ratios exceed the critical cutoff level $1 + \lambda$, are assumed to sign contracts to install buffers on all of their surface water frontage. Marginal agents, i.e., those whose benefit-cost ratios equal the critical cutoff level $1 + \lambda$, are assumed to sign contracts to install buffers on as extensive a portion of the parcel's surface water frontage as the budget allows.

Agents observe a random shock each year and decide whether it is more profitable to remain in the program or opt out of their contracts prematurely, based on the annual payments received, the penalty structures they face, the opportunity cost of foregone crop returns from remaining in the program, and the cost of converting the buffer area back to crop production. We use the estimated distribution of random shocks to estimate the probability that each agent remains in compliance with the signed contract prior to each year during the contract lifetime, as given by equation (13). In the first two scenarios, agents face payment of the standard penalty in deciding whether to opt out of their contracts before their termination dates. In the third scenario, agents face payment of the optimal penalty in deciding whether to terminate their contracts prematurely.

We calculate the total acreage on which riparian buffers are installed under contract, the expected average number of acres with riparian buffer acres remaining at the end of the 10-year contract period, and water quality benefits net of opportunity costs (net water quality benefits) for four budget levels: \$0.25 million, \$1 million, \$5 million, and \$15 million.

3.2 Simulation Results

Table 1 summarizes the results of our numerical analysis. As expected, buffer acreage and net program benefits both increasing in budget size under all three scenarios. The percentage of contract acres reconverted to cropland prior to the 10-year contract expiration date is also increasing in budget size. This latter result is also as expected: Greater budgets reduce the shadow price of funds and thus lower the cutoff level under each scenario, allow the principal to offer contracts to agents with lower benefit-cost ratios, i.e., with lower water quality benefits and higher opportunity costs. Random shocks to opportunity costs make it more likely that these agents' opportunity costs will exceed contract payments (which are fixed at the time contracts are signed) and thus that they will choose to opt out of their contracts prematurely.

In what follows, we concentrate on the ways in which adjusting benefit-cost ratios for the possibility of premature termination affects program performance, as measure by participation in the buffer program, the percentage of buffer acres reconverted to cropland prior to the 10-year contract expiration date, and net water quality benefits.

Program size. Adjusting benefit-cost ratios for the possibility of premature contract exit has relatively small effects on program size, as indicated by the acreage of buffers receiving CREP contracts: There is less than a 1% difference in buffer acreage under contract in each of the three scenarios. There are, however, significant differences in which agents receive contracts at the margin and in contract completion, at indicated by differences in rates of premature contract termination and net water quality benefits, as discussed below.

Premature contract termination. The percentage of buffer acres converted back to cropland prior to the 10-year contract termination date under the standard benefit-cost ranking procedure is similar to premature termination rates reported in the literature for CREP and EQIP

(Cattaneo 2003, Kim et al. 2022). Adjusting benefit-cost ratios for the possibility of premature contract termination reduces the percentage of buffer acres exiting the program prior to the contract expiration date when that adjustment is made using either the standard or the optimal penalty. Reductions in premature exit achieved with adjustments made using the standard penalty are quite modest. Reductions in premature exit achieved with the optimal penalty are more substantial. Exit rates under the optimal penalty scenarios are reduced to zero at low budget levels and are less than half of those experienced when projects are ranked ignoring the possibility of premature exit or when benefit-cost ratios are adjusted for the possibility of premature exit using exit probability under the current standard penalty.

Intuitively, the optimal penalty generally starts high and falls gradually over the term of the contract. As a result, it deters early exit. Further, it helps select agents who are more likely to find it in their interest to remain in compliance with contract terms for the entire length of the contract. The standard penalty, in contrast, starts low and grows over time. It thus both incentivizes early exit and helps select agents more likely to opt out of their contracts prematurely. This latter point also explains the small size of the reduction in early exit when benefit-cost ratios are adjusted for the possibility of early exit using the standard penalty, especially since agents are assumed to face the standard penalty when contracts are offered on the basis of benefit-cost ratios that are not adjusted for the possibility of early exit.

Net water quality benefits. Also as expected, program performance, as measured by net water quality benefits, is greater when the penalty structure is optimized and the optimal penalty structure is used to adjust benefit-cost ratios for the possibility of premature contract termination. That performance advantage is increasing in budget size and thus becomes substantial with large budgets. Net water quality benefits under the scenario using the optimal penalty structure are 1%

greater than net water quality benefits under the scenario when benefit-cost ratios are not adjusted for the possibility of premature contract termination with a 10-year budget of $0.25 million. The relative improvement in net water quality benefits rises to 2% at a 10-year budget of $1 million, 5% with a 10-year budget of $5 million, and 11% with a budget of $15 million.

Adjusting benefit-cost ratios for the possibility of premature contract termination using the standard penalty also results in greater net water quality benefits relative to ranking projects without taking the possibility of premature contract termination into account. As with riparian buffer acres and premature exit rates, these increases in water quality benefits are quite small. As discussed above, the standard penalty structure is not highly effective at preventing premature exit, so that taking the possibility of premature contract termination into account in ranking projects has relatively little effect on water quality benefits as well as selection of agents and buffer acreage initially under contract.

4. CONCLUSION

The literature on efficient targeting of long-term projects in PES programs like the CRP and CREP consistently finds that projects should be ranked according to their ratios of benefits to costs and then selected in descending order until a budget or acreage constraint binds. This selection rule has been shown to be robust to numerous complicating factors as well as when benefits are measured in terms of quantities of ecosystem services rather than their monetary values. These analyses derive static benefit-cost ratios under an implicit assumption of perfect completion of long term PES contracts, ignoring aspects of imperfect compliance such as withdrawals prior to contract expiration dates.

This paper shows theoretically how benefit-cost ratios should be modified to incorporate the possibility of premature contract termination and investigates the factors that determine how incorporation of premature contract termination probabilities alters benefit-cost ratio project rankings. We then use a numerical model of the CREP riparian buffer program to investigate the extent to which performance can be improved by incorporating the possibility of premature contract termination into project selection criteria. Preliminary results from a major agricultural county in Maryland indicate that adjusting benefit-cost ratios for the possibility of early termination reduces rates of early termination and increases net water quality benefits. These improvements in performance are increasing in budget size. They are modest under the current standard penalty structure but become economically significant when the penalty for premature contract termination optimized. Additionally, relative improvements in program performance are increasing in program size as long as budget constraints remain binding.

These results likely constitute an initial low-end estimate of potential improvements in program performance, as they derive from a study of a single county with relatively homogeneous agents and only modest variation in water quality benefits. We expect to find greater improvements in potential performance in the near future as we expand the numerical analysis to all portions of Maryland within the Chesapeake Bay watershed, which contain a more heterogeneous set of agents and exhibit greater variation in water quality benefits.

References

Babcock, B. A., Lakshminarayan, P. G., Wu, J., & Zilberman, D. (1996). The economics of a public fund for environmental amenities: a study of CRP contracts. American Journal of Agricultural Economics 78(4), 961–971.

Baylis, K., Coppess, J., Gramig, B. M., & Sachdeva, P. (2022). Agri-environmental programs in the United States and Canada. Review of Environmental Economics and Policy 16(1), 83-104.

Belt, K., Groffman, P., Newbold, D., Hession, C., Noe, G., Okay, J., Southerland, M., Speiran, G., Staver, K., & Hairston-Strang, A. (2014). Recommendations of the Expert Panel to Reassess Removal Rates for Riparian Forest and Grass Buffers Best Management Practices.

Cattaneo, A. (2003). The pursuit of efficiency and its unintended consequences: contract withdrawals in the environmental quality incentives program. Applied Economic Perspectives and Policy, 25(2), 449–469.

Choi, D. S., Ready, R. C., & Shortle, J. S. (2020). Valuing water quality benefits from adopting best management practices: A spatial approach. Journal of Environmental Quality, 49(3) 582–592.

Claassen, R., Cattaneo, A., & Johansson, R. (2008). Cost-effective design of agri-environmental payment programs: US experience in theory and practice. Ecological economics 65(4), 737-752.

Engel, S. (2016). The devil in the detail: a practical guide on designing payments for environmental services. International Review of Environmental and Resource Economics, 9(1–2), 131–177.

Feather, P. M., & Hellerstein, D. R. (1999). Economic valuation of environmental benefits and the targeting of conservation programs: The case of the CRP (Issue 778). US Department of Agriculture, ERS.

Hansen, A. T., Campbell, T., Cho, S. J., Czuba, J. A., Dalzell, B. J., Dolph, C. L., Hawthorne, P. L., Rabotyagov, S., Lang, Z., & Kumarasamy, K. (2021). Integrated assessment modeling reveals near-channel management as cost-effective to improve water quality in agricultural watersheds. Proceedings of the National Academy of Sciences 118(28), e2024912118.

Hellerstein, D.M., 2017. The US Conservation Reserve Program: The evolution of an enrollment mechanism. Land use policy 63, 601-610.

Kim, Y., Lichtenberg, E., & Newburn, D. (2022). Payments and Penalties in Ecosystem Services Programs. http://doi.org/10.22004/ag.econ.322103

Lang, Z., Rabotyagov, S. S., Cho, S. J., Campbell, T., & Kling, C. L. (2020). Good Seeds Bear Good Fruit: Using Benefit-to-Cost Ratios in Multiobjective Spatial Optimization under Epistasis. Land Economics 96(4), 531–551.

Lee, K.-H., Isenhart, T. M., & Schultz, R. C. (2003). Sediment and nutrient removal in an established multi-species riparian buffer. Journal of Soil and Water Conservation 58(1), 1–8.

Price, E., Fleming, T., & Wainger, L. (2021). Cost Analysis of Stormwater and Agricultural Practices for Reducing Nitrogen and Phosphorus Runoff in Maryland. https://doi.org/10.13140/RG.2.2.28896.74246/1

Rabotyagov, S. S., Campbell, T. D., White, M., Arnold, J. G., Atwood, J., Norfleet, M. L., Kling, C. L., Gassman, P. W., Valcu, A., & Richardson, J. (2014). Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. Proceedings of the National Academy of Sciences 111(52), 18530–18535.

Reichelderfer, K., & Boggess, W. G. (1988). Government decision making and program performance: the case of the conservation reserve program. American Journal of Agricultural Economics 70(1), 1-11.

Ribaudo, M. O. (1989). Targeting the conservation reserve program to maximize water quality benefits. Land Economics 65(4), 320–332.

Sweeney, B. W., & Newbold, J. D. (2014). Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. Journal of the American Water Resources Association 50(3), 560–584.

Wu, J., Zilberman, D., & Babcock, B. A. (2001). Environmental and distributional impacts of conservation targeting strategies. Journal of Environmental Economics and Management 41(3), 333–350.

Figure 1. Timing of an Agent's Decisions in a Two-period PES Contract

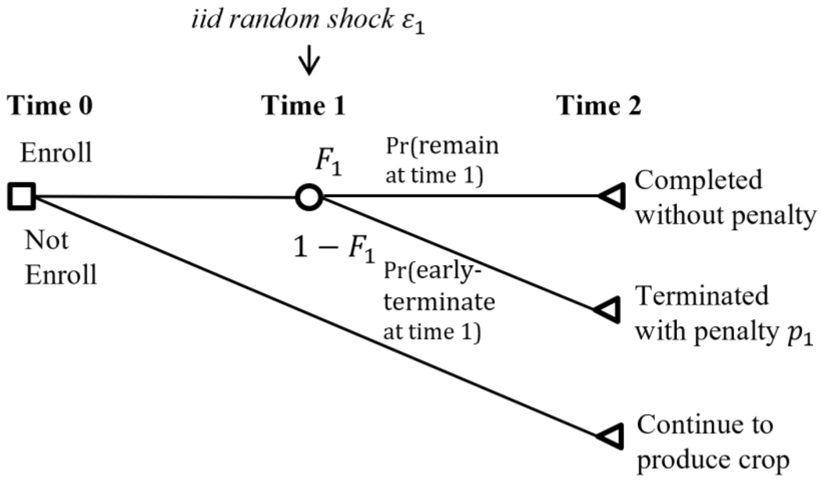

Table 1. Numerical Simulation Results

Ten-Year Budget	Standard Benefit-cost Ratio Ranking (Scenario 1)	Benefit-cost Ratio Ranking Adjusted for Exit, Standard Penalty (Scenario 2)	Benefit-cost Ratio Ranking Adjusted for Exit, Optimal Penalty (Scenario 3)
Panel A. Acres of Riparian Buffer under Contract			
$0.25 million	232.8	233.3	233.0
$1.00 million	735.3	735.5	736.0
$5.00 million	2,665.7	2,687.5	2,658.2
$15.00 million	5,798.3	5,800.3	5,729.1
Panel B. Percent of Contract Acres Exiting Before Termination Date			
$0.25 million	0.68	0.66	0.00
$1.00 million	1.32	1.16	0.00
$5.00 million	3.98	3.85	0.00
$15.00 million	7.59	7.59	0.19
Panel C. Net Water Quality Benefits			
$0.25 million	$1,395,600	$1,395,784	$1,406,877
$1.00 million	$4,019,573	$4,022,647	$4,082,928
$5.00 million	$11,959,426	$11,964,220	$12,558,776
$15.00 million	$20,625,060	$20,625,242	$22,865,257