Integrated Assessment Modeling for Design of Riparian Buffer Systems and Incentives for Adoption

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ABSTRACT

Installation of riparian buffers on agricultural land has become a high priority for policy-makers seeking to reduce nutrient and sediment loads from agriculture, particularly in the Chesapeake Bay watershed. However, riparian buffers are costly with strict buffer design requirements and restrictions often seen as a barrier to adoption. This study addresses two key policy questions. First, to what extent does flexibility in buffer design improve the probability of adoption by farmers? Using a dynamic optimization land-conversion model we find that increased payments for ecosystem services (PES) and smaller penalties for exiting a contract increase the adoption of grass buffers. The second policy question is given that farmers will maximize their own private benefits, how can buffer contracts be designed so that they will be adopted by farmers and offer the highest environmental benefits at the lowest costs? We develop a directed acyclic graph (DAG) where farmers maximize profits by choosing dynamically the best path of land-use decisions and the contracts offered by the government. Our results indicate that state(and path-)-dependent payments to farmers can encourage the adoption of grass, shrub, and forested riparian buffers. State-dependent PES can reduce the cost to the government of riparian buffers by 20-40% for shrub and grass buffers, respectively. However, the forested buffers require higher PES than the value of the water quality benefits that they provide.

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INTRODUCTION

Agricultural nutrient loadings to streams contribute to the severe impairment of surface water quality in the Chesapeake Bay watershed. Due to increasing pressure to protect freshwater resources and achieve local and regional water quality goals, farmers in the U.S. are encouraged to adopt best management practices (BMPs) to reduce nutrient runoff and sediment losses from agricultural landscapes. For example, riparian buffers are zones of vegetation located adjacent to streams and riverbanks that act as barriers between agricultural land and waterbodies. Riparian buffers can be highly effective in capturing and filtering nonpoint source (NPS) pollutants from surface runoff (Lowrence et al. 1997; Lee, Isenhart and Schultz 2003; Weller, Baker and Jordan 2011; Schilling and Jacobson 2014) while also providing various other ecosystem services such as wildlife habitats (Lyons, Trimble and Paine 2000; Talmage et al. 2002) and erosion prevention and flood control (Lyons, Trimble and Paine 2000; Stutter, Chardon and Kronvang 2012).

Because of the effectiveness in NPS pollutants removal and the functionality in provision of ecosystem services, riparian buffers are increasingly drawing interest from government agencies and local stakeholders. Particularly, the installation and management of riparian buffers are considered as key policy tools in the Chesapeake Bay watershed (including Delaware, Maryland, New York, Pennsylvania, West Virginia and the District of Columbia) where Watershed Implementation Plans (WIPs) have been developed to help meet the requirements of the Chesapeake Bay Total Maximum Daily Load (TMDL). For example, Pennsylvania relies on riparian buffer restoration on farmland to achieve 16.5 percent of its nitrogen reduction goals. A total of 64,847 acres of forest and grass buffers were installed by 2015 to meet its Phase I WIP goal. The long-term goal in Pennsylvania is to plant 72,500 acres of riparian buffers by 2017, and to have 205,698 acres of riparian buffers installed by 2025 to meet the TMDL requirements (Chesapeake Bay Commission 2016).

However, riparian buffers are costly. For example, Shortle et al. (2013) report that the annual costs to landowners for forest buffers are $258.38 per acre per year and for grass buffers are $122.67 per acre per year in Pennsylvania[10]. This cost includes installation, maintenance and continuous management efforts over a long period of time (i.e., 10-15 or more years), and the opportunity cost of the forgone agricultural productivity. Additional costs include the lost option value of not being able to use a land parcel in the best use in the future and changes in non-market benefits[11] such as aesthetics and cultural norms. Moreover, buffer design requirements and restrictions may increase opportunity costs further hindering the adoption of buffers by farmers.

The available options of buffer designs and management requirements are limited under current incentive programs and contracts for implementation of riparian buffers such as the Conservation Reserve Enhancement Program (CREP) by the federal government and the Resource Enhancement and Protection (REAP) program in Pennsylvania. To be ecologically effective and locally non-invasive, certain vegetation species and minimal widths are required. Additionally, buffer vegetation requires long periods of time to develop and reach full environmental effectiveness, especially for forested buffers; hence, participating farmers must commit to long-term contracts. They encounter increased risks related to developments in agricultural commodity and land markets, and possibilities to generate private benefits from buffers become quite limited. Buffer harvesting, foraging or grazing is restricted by contract terms because buffer effectiveness in mitigating nutrient loads can be hampered by routine human or animal activities. The vegetation

[10] Estimates are from the Abt/USEPA cost estimates from the Natural Resource Conservation Service (NRCS) financial assistance payment schedules with minor adjustments.
[11] The changes in non-market benefits could be benefits for landowners rather than costs indicating that buffers provide more private non-market values (such as increased recreational opportunities) than the current land use.

species to be planted, the maintenance routine and management of the buffers are guided by government-approved conservationists and a uniform conservation plan (see USDA FSA 2015), which are all often subject to quite rigid standards. Hence, with current incentive programs and contracts, the riparian buffers under contract can only provide the participating farmers with limited private benefits besides the contract payments, while farmers have little freedom in buffer design.

In a survey sent to 500 riparian landowners in Centre County, Pennsylvania in 2009 with 175 completed responses (35% response rate), riparian landowners reported that the top two incentives that would increase their willingness to install a riparian buffer were if "a buffer reduced streambank erosion" and if "you had a say in designing your buffer" (Brooks et al., 2011). Given that riparian buffers can provide various environmental and ecological services while the implementation of riparian buffers can create economic challenges for landowners, in this paper we examine how BMPs can be designed to allow flexibility to improve adoption rates while achieving the desired environmental outcomes. To this end, we investigate two key policy questions.

First, to what extent does flexibility in buffer design improve the adoption rates by farmers? Flexible buffer designs enable farmers to select from a wider array of options for buffer size, vegetation types, spatial arrangement, contract lengths, and payment schedules. We develop a dynamic land-use conversion model (see Song et al. 2011 and Li and Zipp *forthcoming*) to model the economic tradeoffs of converting active agricultural land to one of five riparian buffers designs that vary by the size of the buffer and the vegetation type (grass or trees). Optimal land-use decisions are made based on pairwise comparisons between the expected payoffs from agricultural use versus the PES of the incentive program. We model three payment schedules – (1) uniform

CREP payments, (2) targeted PES based on water quality benefits to the Chesapeake Bay estimated using a combination of the Soil Water Assessment Tool (SWAT) and the Riparian Ecosystem Management Model (REMM), and (3) targeted PES with strict penalties for exiting the 15-year contract early.

Results suggest that under uniform CREP payments there will be little to no installation of riparian buffers. This conforms to anecdotal evidence that farmers lose money when they install riparian buffers under current policies and adoption is driven by non-monetary concerns. Buffer contracts with targeted PES induce significantly more buffer installations. Our SWAT and REMM results suggest that the Chesapeake Bay water quality benefits are highest for grass buffers. Given that grass buffers are also cheaper to install and maintain, it is not surprising that our results suggest that farmers will install more grass buffers than forested buffers. Buffer contracts with penalties for exiting reduce the buffer acreage by more than half.

A second modeling question is: given that farmers will maximize their own private benefits, how can buffer contracts be designed so that they will be adopted by farmers and offer the highest environmental benefits at the lowest costs? In this work we develop a model where farmers maximize profit by dynamically choosing the best path of land-use decisions and the contracts offered by the government. The government's objective is to maximize the environmental benefits from farmers' choice of land-use paths at the lowest cost. The expected environmental benefits of these buffers are estimated using a combination of the Soil Water Assessment Tool (SWAT) and the Riparian Ecosystem Management Model (REMM).

We present this problem a well-known problem in graph theory and corresponds to finding the longest (most profitable) path in a directed acyclic graph (DAG), which identifies the optimal land-use paths maximizing farmers' profits and the associated environmental benefits for any buffer contract design. Then, we randomize the contract payments and among the randomly distributed payments we find the minimum contract payment necessary to provide the highest environmental benefits. With such predictions in hand, landowners can achieve desired adoption benefits (with reduced adoption barriers) and maximal, or close to maximal, ecosystem service benefits at local, regional, and watershed scales. At least theoretically, one may consider the combinatorial optimization problem that identifies the minimum payments for buffer installation for maximum farmer profits and maximum environmental benefits. This, however, is an optimization problem with computational complexity which grows exponentially with the number of contracts. Computationally feasible approximations of this complicated problem are possible, and one of them is using random choice of contract values as we describe in this manuscript. It is also possible to use more accurate and much more complex approximations, albeit they fall beyond the scope of this paper and are subject of current and future research. Our results indicate that state(and path-)-dependent payments to farmers can encourage the adoption of grass, shrub, and forested riparian buffers. State-dependent PES can reduce the cost to the government of riparian buffers by 20-40% for shrub and grass buffers, respectively. However, the forested buffers require higher PES than the value of the water quality benefits that they provide.

The rest of the paper will proceed as follows: (1) we introduce the data, study area, buffer designs, and water quality benefit modeling; (2) we use these data to solve a dynamic optimization model to investigate the extent flexibility in buffer design improves the adoption rates by farmers; (3) we also use these data to solve a directed acyclic graph (DAG) to find the land-use decision paths that maximize farmer profits and water quality benefits at the lowest PES.

DATA

Study site under current conditions

The studied region, Spring Creek watershed with an area of 370 km^2 (91,428 acres), is located in the Ridge and Valley Province in Centre County, Pennsylvania (see Figure 1). The watershed land use is 34% agriculture, 23% developed, and 43% forest. Within 200 feet of the streams, 26% of the area is in agricultural land use, of which 15% is used for hay production, 4% is used for corn-soybean rotation and 7% is used for other crop rotations. The average size of agricultural parcels with riparian land is 160 acres.

Corn-soybean rotations and hay production are the major agricultural activities due to the dairy industry in this watershed. Annual average prices for corn, soybeans and hay in Centre County, PA in 1999-2013 are obtained from USDA NASS database. Annual average yields for corn-soybeans rotation[12] and hay are generated from Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) simulations. Hence, annual average returns per acre for the farmer are calculated as the products of the NASS prices and SWAT-predicted yields (Table 1).

Models for simulating nutrient reduction

In this study, SWAT was used to simulate crop yields and the loss of water, nutrients, and sediment from riparian agricultural fields under different crop rotation management scenarios. SWAT (Arnold et al., 1998; Srinivasan et al., 1998) is a widely used water quality model to predict the discharge, nutrient and sediment loss and crop yield in a watershed as a function of climate,

[12] The soybeans yields in the simulated corn-soybeans rotation are relatively low than the annual average soybeans yields in Centre County's historical data, partly due to the fertilizer inputs restrictions, and the high volatility in weather and hydrological conditions.

topography, soils and management practices. SWAT divides the watershed into subbasins according to the hydrological routines and topography and then divides each subbasin into hydrological response units (HRUs), which are the unique combinations of land use, soil and slope. Thus, all areas assigned a given HRU will have identical hydrological properties despite their physical locations in the subbasin.

The Riparian Ecosystem Management Model (REMM, Lowrance and Altier, 2000) was used to estimate the effectiveness of the five buffer designs (see Table 2) in reducing and sequestrating the nutrient and sediment runoffs from upland, as simulated by SWAT. REMM (Lowrance and Altier, 2000; Inamdar et al., 1999) is a field-scale, process-based, two-dimensional model to simulate the water quality benefit provided by riparian buffers. REMM sets up a three-zone buffer system where Zone 1 is nearest to the stream and Zone 3 is farthest and then simulates the interaction between vegetation, hydrology, nutrients, sediments and soils in each buffer zone. In this way, it tracks the transport of water, nutrient and sediment through each buffer zone and eventually from buffer system to the stream. Both SWAT and REMM run at a daily time scale. Surface runoff, nutrient and sediment loads simulated by SWAT were used as input to REMM, such that the benefits of the riparian buffer could be explored for various land management scenarios. Here, we explored how two crop rotations (corn/soybeans and hay) affected the performance of five riparian buffer designs.

Buffer designs, costs, and nutrient reductions

We consider five buffer designs in this study varying by width, vegetation type, and arrangement: (1) 10 meters (32.8 feet) of grass; (2) 15 meters (49.2 feet) of grass; (3) 15 meters (49.2 feet) of trees; (4) 6 meters (19.7 feet) of grass and 24 meters (78.7 feet) of trees; and (5) 30 meters (98.4 feet) of grass. These five buffer scenarios were developed based on the minimum buffer width to participate in CREP and also recommended buffer designs by PA stormwater BMP manual (DEP, 2006). Table 2 summarizes the details of land uses in the study region (Spring Creek watershed) and the buffer designs.

We designed four PES compensation scenarios for these buffers. First, we used the approximated CREP payment rates[13] in Centre County, PA as an example of uniform PES compensation scenario that pays on average $210 per acre of riparian buffer installed (see Table 3). Second, we designed a targeted PES compensation scenario. Specifically, the PES rate was determined by the products of the nutrient reduction rates (see Table A-1 in Appendix A) for the buffer designs and the per unit monetary values of the nutrient reductions. Ready et al. (n.d.) suggested that the values of nutrient and sediment reductions in the Chesapeake Bay are, respectively, $14.96 per pound for nitrogen, $181.61 per pound for phosphorus, and $0.34 per pound for total sediment[14]. Third, we used the targeted PES compensation and introduced a penalty for exiting the buffer incentive program. Buffer contracts lengths are typically 10-15 years with penalties for exiting the contract early. For simplicity, we assume that the penalty is equal to twice the annual average PES payment. Finally, we create a flexible payment schedule that depends on the state of the riparian buffer (early establishment stage, middle stage, fully developed stage), the full path of land-use decisions, and the length of the contract.

[13] The detailed data of CREP payments are not publicly available. According to a guide for CREP participants in Pennsylvania, the average CREP payment rate is about twice the rental rates of the land parcels (PACD 2009).
[14] Moore et al. (2015) use a choice experiment to measure the value of water improvements to the Chesapeake Bay, and Ready et al. (n.d.) used the same model and suggest an average value per household of $43.37 and a total value of all households of $1.98 billion. The total values are assigned by water quality index weights among nitrogen (weight = 0.36), phosphorus (weight = 0.36) and total sediment (weight = 0.28), and also following the TMDL goals.

TO WHAT EXTENT DOES FLEXIBILITY IN BUFFER DESIGN IMPROVE THE ADOPTION RATES BY FARMERS?

Dynamic Land-Use Conversion Model

We develop a dynamic land-use conversion model to answer this research question with an application in Centre County, Pennsylvania. We assume that farmers make a land-use decision in each period *t* between two alternatives based on the relative comparisons of the monetary values of the expected payoffs. For example, they can choose either "a riparian buffer" (B_{yes}) with payoff $\pi_{yes}(t)$ or "agricultural land use and no buffer" (B_{no}) with payoff $\pi_{no}(t)$. If the current land use is in B_{yes} and the farmer initiates conversions to the other alternative B_{no}, a conversion cost C_{yn} will be incurred[15], or vice versa. The payoffs of land-use alternative $l \in \{B_{yes}, B_{no}\}$ in period *t* is denoted by $\pi_l(t)$ and follows a geometric Brownian motion (GBM) stochastic process with a general evolution form with drift term μ_l and variance σ_l, in the following return equation:

$$d\pi_l(t) = \mu_l(\pi_l, t)dt + \sigma_l(\pi_l, t)d\varepsilon_l, \qquad l \in \{B_{yes}, B_{no}\} \tag{1}$$

where $d\varepsilon_l$ is the increment of a Wiener process[16] which allows farmers to learn about and predict future returns in each new period based on information updated in previous period. The correlation coefficient between B_{yes} and B_{no} is denoted as ρ, such that $\mathrm{E}\left[d\varepsilon_{yes} d\varepsilon_{no}\right] = \rho dt$.

Farmers' expected net present value (NPV) payoffs from land use i at period *t* is denoted $V^l\left(\pi_{yes}(t), \pi_{no}(t)\right)$, which depends on the distribution of future returns of both land uses and on

[15] The average conversion cost from agricultural land to riparian buffers is $107.43 per acre if converted to grass buffers (USDA NRCS 2013), and $174.40 if converted to forest buffers (Tyndall and Bowman 2016). The average conversion cost from riparian buffers to agricultural land in general condition is $47 per acre (Williams et al. 2010).

[16] The Wiener pdf is $f_{W_t}(x) = \frac{1}{\sqrt{2\pi t}}\exp(-\frac{x^2}{2t})$, following normal distribution with zero mean and variance *t* at any fixed period *t*. The covariance between any s and *t* is $cov(W_s, W_t) = \min(s,t)$, and $corr(W_s, W_t) = \sqrt{\frac{\min(s,t)}{\max(s,t)}}$.

the distribution of decisions made to either keep the current land use l or convert it into the other alternative k, where $l, k \in \{B_{yes}, B_{no}\}$ and $l \neq k$. The NPV payoffs are depicted in a generalized value function V (see Song et al. 2011) as follows:

$$V^l\left(\pi_{yes}(t), \pi_{no}(t)\right) = max\begin{Bmatrix}\pi_l(t)dt + e^{-rdt}EV^l[\pi_{yes}(t+dt) \times \pi_{no}(t+dt)], \\ V^k\left(\pi_{yes}(t), \pi_{no}(t)\right) - C_{lk}\end{Bmatrix} \quad (2)$$

ere r is the discount rate. Equation (2) indicates that the land-use decision for farmers is made based on the comparison between the expected return from keeping the same land use l in the next period (the first term in the brackets), and the expected return from switch to alternative k less the conversion cost C_{lk} (the second term in the brackets), $l, k \in \{B_{yes}, B_{no}\}$ $and\ l \neq k$.

In order to optimally solve the dynamic land use decision problem in Equation (2), for value functions V^l and V^k, $l, k \in \{B_{yes}, B_{no}\}$ and $l \neq k$, the land-use decisions in each period t must satisfy the following conditions: either the value function of payoff for the current land use l is positive (Equation 3), or the value function of payoff for the current land use l is no less than that of the alternative k less the conversion cost (Equation 4). That is,

$$LV^l\left(\pi_{yes}(\mathrm{t}), \pi_{no}(\mathrm{t})\right) \geq 0, l, k \in \{B_{yes}, B_{no}\} \quad (3)$$

where $LV^l\left(\pi_{yes}(\mathrm{t}), \pi_{no}(\mathrm{t})\right)$ is the second order Taylor expansion of $V^l\left(\pi_{yes}(t), \pi_{no}(t)\right)$ by applying Ito's lemma, such that

$$LV^l\left(\pi_{yes}(\mathrm{t}), \pi_{no}(\mathrm{t})\right) = rV^l(\pi_{yes}, \pi_{no}) - \pi_l(\mathrm{t}) -$$

$$\sum_{s=yes,no} \alpha_s(\pi_s, \mathrm{t}) \frac{\partial V^l}{\partial \pi_s} \sum_{s=yes,no} \frac{\sigma_s^2(\pi_s, \mathrm{t})}{2} \frac{\partial^2 V^l}{\partial \pi_s \partial \pi_s} - \rho \sigma_{yes}(\pi_{yes}, \mathrm{t}) \sigma_{no}(\pi_{no}, \mathrm{t}) \frac{\partial^2 V^l}{\partial \pi_{yes} \partial \pi_{no}}$$

$$V^l\left(\pi_{yes}(t), \pi_{no}(t)\right) \geq V^k\left(\pi_{yes}(t), \pi_{no}(t)\right) - C_{lk}, l, k \in \{B_{yes}, B_{no}\}\ and\ l \neq k \quad (4)$$

Either (3) or (4) holds with strict equality. (5)

Estimation

The empirical method to solve the dynamic land use model involves three steps. First, we estimate the GBM parameters in equation (1). We use the following estimating equation after linearizing equation (1) and taking the discrete approximation of the intertemporal return difference:

$$\ln \pi_{lt} - \ln \pi_{l(t-1)} = \alpha_l + \sigma_l \xi_l, \quad l \in \{B_{yes}, B_{no}\} \tag{6}$$

where $\alpha_l = \mu_l - \frac{\sigma_l{}^2}{2}$, and the error term ξ_l follows standard normal distribution. The parameters α_l, σ_l and ρ can be estimated by maximum likelihood method (see Song et al. 2011).

Second, the model is solved by collocation using OSSOLVER (Fackler, 2004) and estimated with the CompEcon package in MATLAB (Miranda & Fackler, 2004). The value functions are approximated using a linearized combination of a sequence of known basis functions. The optimal decision rule is determined by solving and evaluating the approximated value functions at a pair of land use alternatives $\{l, k\}$ as well as the return less the conversion costs, and based on the results the conversion strategy payoffs are then compared with the status-quo strategy payoffs (Fackler, 2004). A piecewise linear spline function is used as the family basis function, with the nodal points as the corresponding pairs of simulated returns for each state variable (NPV return for each land use type) evenly spaced over the revenue interval between $0 and $1000, with an increment of $10. Results for each pair of land use alternatives can be presented in a graph of pairwise optimal conversion boundaries $\{b_{lk}(\pi_l(t)), b_{kl}(\pi_k(t))\}$. These boundaries determine the payoffs necessary to induce conversion from “agricultural land use and no buffer” to “a riparian buffer” given the payoffs the farmer can earn from using the land for agricultural productions, or vice versa. For example, for a land parcel currently in agricultural production in period t, if we find that $b_{no,yes}(\pi_{no}(t)) > \pi_{yes}(t)$, i.e. the expected net return from installing buffers does not attain the required amount for conversion, then the land is kept in agricultural production. On the other hand, if $b_{no,yes}(\pi_{no}(t)) \leq \pi_{yes}(t)$, i.e., then the land would be converted from agricultural land to riparian buffers.

Third, the simulation results enable predictions to be generated on the proportions of land parcels currently used for agricultural production that will be converted for buffer installations in a given year. The procedure follows the methods described in Song et al. (2011). Starting with the base year returns as the initial period (Year 1) returns, the estimated parameters from the GBM process in Equation (6) are used to generate N = 5,000 Monte Carlo randomly drawn sample paths of joint returns for a pair of land use alternatives $\{l, k\}$ over a fifteen-year time horizon[17]: $\{\pi_l(\mathrm{t}), \pi_k(t)\}, t = 1, \ldots 15$. Following the same decision rule of optimal land-use conversions, in each year the returns for each sample path are compared with the corresponding conversion boundaries, and it is determined if the current land use should be converted to the alternative land use or remain unchanged. The comparisons are iterated for each sample path over the fifteen-year period and the number of land parcels being converted to buffers for each period (M) is predicted. The predicted proportion of land being converted from agricultural land to buffers in each year is then obtained from dividing M by N.

Results

The estimated GBM parameters (see Appendix) are used to generate N = 5,000 Monte Carlo randomly drawn sample paths of joint returns in T = 15 years for each of the ten groups of pairwise

[17] The fifteen-year time horizon is determined as the CREP program contract length is usually 15 years (USDA FSA 2016).

land uses (five buffer designs and two cropping systems). The proportions of land used for buffer installations converted from land previously used for corn-soybeans or hay in each group is predicted for the 15-year period by comparing the returns to each land use to the optimal switching boundaries (see Appendix for graphs of the switching boundaries). Both 1999 and 2013 are used as base years for comparisons. The aggregate acreage of buffers installed in each year is the sum of the acreage of buffers converted from agricultural land in corn-soybeans rotation and hay in each year. The aggregate results are shown in Figure 2.

With uniform CREP payments, the predicted buffer installations are relatively low. No corn-soybeans rotations or hay land is converted to either buffer designs in the short term (Years 1-6). In the long term, a small amount of corn-soybeans rotation land would be converted to buffers starting in Year 7, with the maximum installations in Year 10, and little growth in Years 11-15. No land currently in hay production is predicted to converted to buffers even in the long term. Hence, it is likely that the uniform CREP payments offer less than sufficient incentives to encourage buffer installations.

With targeted payments, for simulation results starting from either base year (1999 or 2013), Buffer 2 has the highest predicted installation. Given the prediction of 693 acres and 936 acres of 50-foot wide grass buffers predicted with base year 1999 and 2013, respectively, the sediment and nutrient reduction rates are estimated by the SWAT and REMM simulations during a 15-year period (1999 - 2013) (see Table A-1 in Appendix A). Figure 3 shows the parallel comparisons of annual nutrient reductions among the five buffer designs in the 15-year period. For simulation results starting from base year 1999, Buffer 2 has the overall highest annual reductions of nitrogen, phosphorus and sediment. For simulation results starting from base year 2013, Buffer 2 has the overall highest annual reductions of all three pollutants in Year 1-10, while Buffer 5 starts to have equal or higher annual reductions than Buffer 2 after Year 11. In both simulations, it can be observed that the maximum of reductions of all three pollutants happens in Year 13, and there are also two secondary peaks of reductions happen in Year 5 and Year 10. In sum, the results suggest that Buffer 2 has the overall highest efficiency in reducing the three pollutants in both the short term (Years 1-5) and long term (beyond Year 10), while Buffer 5 is equally efficient in the long term. The fact that the overall peak of pollutant reductions happens in Year 13 also imply that the installation and maintenance of riparian buffers may take a relatively long term in order for the buffers to develop to their maximum performance levels. Table 4 summarizes the annual average aggregate abatement costs (calculated as the sum of PESs) and pollutant reductions by each buffer design.

If Buffer 2 is chosen as the buffer design to be promoted in the studied region, it would cost $0.41 million on average per year from base year 1999 to achieve buffer installations of 693.38 acres, or $0.66 million on average per year from base year 2013 to achieve buffer installations of 936.01 acres by the end of the fifteen-year horizon. According to USDA FSA (2017), as of January 2017 there are approximately 333 acres of riparian buffers participating in CREP in Centre County, PA. Hence, compared with the actual acreage of riparian buffers in the studied region, our results on the acreage of buffer installations are somewhat overestimated.

With targeted payments and a penalty, the predicted buffer installations are shown in Figure 4, using both 1999 and 2013 as the base year. Compared with the baseline model results, a majority of the land that would be converted to buffers in the baseline model for Buffer 2 are suppressed and will not be converted to buffers at all, hence the predicted buffers in Buffer 2 are largely reduced when penalty is imposed. In particular, after imposing penalty, none of the land in hay production would be converted to buffers with the design of Buffer 2. On the other hand, buffers with the design Buffer 4 (20 feet of grass with 80 feet of trees) shows the highest predicted installations and remain quite stable over the full fifteen-year time horizon. By inspecting the results, it is discovered that once the land in corn-soybeans rotation are converted to buffers with the design Buffer 4, none would be converted back as the necessary payoff from corn-soybeans rotation less the conversion cost and the penalty are far less than being break-even.

If Buffer 4 is chosen as the buffer design to be promoted in the studied region under the additional assumption of penalty for exit, then it would cost $0.25 million on average per year from base year 1999 to achieve buffer installations of 387.01 acres, or $0.25 million on average per year from base year 2013 to achieve buffer installations of 384.51 acres by the end of the fifteen-year horizon. Table 4B summarizes the annual average aggregate abatement costs (calculated as the sum of PESs) and pollutant reductions by each buffer design. This prediction in buffer installations is closer to the actual acreage of riparian buffers in Centre County, PA (333 acres as of 2017). Figure 5 shows the parallel comparisons of annual nutrient reductions among the five buffer designs in the 15-year period with the addition of a penalty.

Discussion

Ninety-five percent of riparian buffer acreage in Centre County, PA is forested due in part to a strong preference at the state level for forested riparian buffers instead of grass buffers. However, results from our dynamic optimization simulations indicate that allowing flexibility in terms of vegetation would significantly increase installation of grass buffers rather than forested buffers. This result is driven by the low maintenance costs of grass buffers compared to forested buffers and the higher Chesapeake Bay water quality benefits of grass buffers. Furthermore, flexibility in the payment schedules suggests that targeted payments instead of uniform CREP payments increase buffer adoption and that longer-term contracts with penalties for exiting reduce buffer adoption. However, in order to better understand how flexibility in payment schedules affects buffer installation decisions, we need an economic model that is not restricted to a year-by-year comparison of farmer profits and can include payments that depend on the state of the riparian buffer (early establishment stage, middle stage, fully developed stage), the full path of land-use decisions, and the length of the contract.

Thus, we also develop a mathematical framework to model farmers' land-use decisions over time that maximizes profits allowing the government to offer flexible payments to achieve water quality benefits in the Chesapeake Bay. This framework explicitly recognizes that the government can offer payments for each riparian buffer state and at each time period which will impact the maximum profits that a farmer can achieve with each land-use decision path.

HOW CAN BUFFER CONTRACTS BE DESIGNED SO THAT THEY WILL BE ADOPTED BY FARMERS AND OFFER THE HIGHEST ENVIRONMENTAL BENEFITS AT THE LOWEST COSTS?

Optimal Land-Use Path in DAG

To answer this research question, we use a well-known problem in graph theory and corresponds to finding the longest (most profitable) path in a directed acyclic graph (DAG). A combinatorial graph $\mathcal{G} = (V, E)$ is characterized by its set of vertices $V = (v, \dots, v_n)$ and the set of its edges. The edges are ordered pairs of vertices (i.e. our graph is directed) and, therefore, we have the inclusion $E \subset V \times V$. For the farmers buffers problem, each of the vertices is labeled by a pair describing the state of the buffer (e.g. no buffer, a grass buffer, a shrub buffer, or a tree buffer) and the time period (e.g. five-year time periods), namely we have

$$v_k = (s_k, t_k), k = 1, \dots, n, \ \ s_k \in \{1, \dots, S\}, \ \ t_k \in \{1, \dots, T\}.$$

A *path* in the graph is a sequence of vertices $\mathcal{L} = (v_{i_1}, \dots, v_{i_m})$ such that any two consecutive vertices on the path are connected by an edge from E. More precisely, $\left(v_{i_j}, v_{i_{j+1}}\right) \in E$, for all $j = 0, 1, \dots, (m-1)$. A path is called a *cycle* if $v_{i_m} = v_{i_1}$. The graph is *acyclic* if it has no cycles. When a weight is associated with every edge in the graph, the graph is called a weighted graph.

In the model, we consider the weights are given by the profits made when deciding to change the state-time from $v_k = (s_k, t_k)$ to $v_q = (s_q, t_q)$. Profits are defined at every edge $e = \left[(s_k, t_k), \left(s_q, t_q\right)\right]$ as

$$\pi_e = A[(p_e y_e - \eta_e)(1 - z_e) + (w_e - c_e)z_e],$$

where A is the (constant) size of an agricultural parcel, p_e are the output (corn, soybean, or hay) prices per yield, y_e are the agricultural yields per area, η_e are the input costs per area, z_e is the proportion of a parcel dedicated to a riparian buffer, w_e are the governmental payments for ecosystem services (PES) provided by the riparian buffer per area, c_e are the maintenance costs for the buffer per area (see Table 5 for these input parameters). In addition to profits, we also have a water quality benefit $\{b_e\}_{e \in E}$ associated with each edge. The realized water quality benefits will be the sum of $\{b_e\}_{e \in E}$ at each edge of the path that maximizes farmers' profits given PES payments w_e.

This framework incorporates all essential elements of our model, in each five-year period $t = 0, 1, 2, 3$, a farmer can choose a buffer state – no buffer ($s = 0$), a grass buffer ($s = 1$), a shrub buffer ($s = 2$), or a tree buffer ($s = 3$) (see Figure 6). The farmer chooses the path that maximizes the sum of his/her profits. Farmers' decision paths have environmental consequences and can provide ecosystem service benefits if buffers are adopted. However, without payments for the provision of these ecosystem services, farmers will underprovide these public goods. The government can provide PES payments at each edge to maximize the ecosystem service benefits provided by farmers' optimal decision paths at the least cost.

Estimation

Given, PES payments w_e, the maximum profit paths are found by first using a depth-first-search (DFS) algorithm to find all strongly connected components in the graph $\mathcal{G}$ (see, e.g. Tarjan 1972 and Gustavson 1976). This gives a topological ordering of the vertices which is then used to find the optimal paths (with respect to profits) following well-known algorithms based on *edge relaxation* (see Cormen et al. 2009 Ch. 24 and references therein). The overall complexity of the algorithm for one set of edge weights is $\mathcal{O}(|V| + |E|)$. The algorithms are implemented using the graph-library in Adler et al. (n.d.).

Results and Discussion

The edge relaxation algorithm (Cormen et al. 2009 Ch. 24) solves for the land-use path across the four time periods that maximizes farmers' profit given PES payments w_e. We simulate $N = 9{,}999$ scenarios by drawing random PES payments from a uniform distribution between \$100/acre and \$200/acre, $w_{e,n} \sim Uniform(100{,}200)\ for\ n = (1, \ldots, N)$. We then select the maximum profit paths with the highest environmental benefits at the lowest costs. These are the paths that farmers will choose because they maximize their profits and the paths the government would choose because they provide the highest environmental benefits per PES payment. If the maximum PES payment is \$200/acre then the only buffer contracts that the farmers would choose are the ones represented in Figure 7 – (1) a grass buffer in $t = (1,2,3)$ (in pink) or (2) a shrub buffer in $t = (1,2,3)$ (in purple). Although shrub buffers provide more total environmental benefits (\$475) compared to grass buffers ($443), the shrub buffers also require higher total PES payments ($394) compared to grass buffers ($318). Therefore, preferred schedule of PES payments is $w_{(0,0),(1,1)} = \$100/acre$; $w_{(1,1),(1,2)} = \$114/acre$; $w_{(1,2),(1,3)} = \$104/acre$. This payment schedule results in farmers choosing the path $(0,0) \rightarrow (1,1) \rightarrow (1,2) \rightarrow (1,3)$ that maximizes their profits and results in the installation of grass buffers in $t = 1,2,3$ with the total monetized water quality benefits equal to $443/acre or $1.39 of benefits for every dollar of PES payments.

In order to induce farmers to select tree buffers, the maximum PES payments need to be increased. We simulate $N = 999{,}999$ scenarios by drawing random PES payments from a uniform distribution between $100/acre and $500/acre, $w_{e,n} \sim Uniform(100, 500)\ for\ n = (1, \dots, N)$. Again, we select the maximum profit paths with the highest environmental benefits at the lowest costs. A few sample paths are shown in Figure 8. However, all paths that lead to forested buffers require more total PES payments than the total value of the water quality benefits to the Chesapeake Bay.

The path to forested buffers that yields the most water quality benefits ($0.76) per dollar of PES payments is $(0,0) \rightarrow (1,1) \rightarrow (1,2) \rightarrow (3,3)$. Thus, the PES payments needed to induce farmers to choose a land-use path that includes forested buffers are greater than the value of the water quality benefits to the Chesapeake Bay. If we consider additional ecosystem services provided by forested buffers such as improved habitat quality and flood and erosion protection, then perhaps forested buffers could pass a cost-benefit analysis. The other paths to forested buffers yield smaller water quality benefits per dollar of PES payments.

The path that commits to forested buffers across all time periods $(0,0) \rightarrow (3,1) \rightarrow (3,2) \rightarrow (3,3)$ and does not allow land-use changes after time period 1, requires an additional $423/acre of total PES payments (or a 58% increase) compared to the path $(0,0) \rightarrow (1,1) \rightarrow (1,2) \rightarrow (3,3)$ and yields only \$0.51 of water quality benefits for every one dollar of PES payments. This suggests that being locked into a 15-year contract (three five-year time periods) is more costly to the farmer than having the flexibility to change contracts every five years and does not produce additional water quality benefits. The path that progresses from grass to shrubs to trees $(0,0) \rightarrow (1,1) \rightarrow (2,2) \rightarrow (3,3)$ yields \$0.59 of water quality benefits for every one dollar of PES payments.

CONCLUSION

The practices of installation, protection, and restoration of riparian buffers are considered of high importance in water quality protection. Particularly, in the Chesapeake Bay area states like Pennsylvania where local water quality as well as the Bay water quality are both severely threatened by the pollutant runoffs, riparian buffers can provide various environmental services. However, the high costs of installation and maintenance of buffers, as well as the high opportunity costs of foregone productivity if the buffers are installed on agricultural land hinders farmers and landowners' adoption of these buffers. The gap between the high demand for better water quality (public goods) and the low private supply of buffers are thus the result of market failure. Hence, environmental regulators and policymakers introduce compensation mechanisms and incentive programs to help farmers and landowners reduce the costs related to buffers and stimulate buffer installations and the provision of public environmental goods.

In this study, we develop two dynamic optimization models to investigate the necessary payoffs for farmers and landowners to adopt buffers, as well as predict the buffer adoption in the long term. This study introduces buffers that are more flexible than the conventional buffers or other BMPs. The buffers vary across with five designs in terms of buffer width, vegetation types and other attributes. Also, farmers and landowners are offered with a more flexible conservation contract as they can decide the optimal timing to adopt buffers in each period over a long term (fifteen years). Lastly, we consider four compensation rates – (1) uniform CREP-type payments, (2) targeted payments that are associated with the performance levels of the water quality benefits to the Chesapeake Bay, (3) targeted payments with a penalty for exit, and (4) state-dependent payments. Results suggest that with these flexible buffers, higher adoptions can be achieved using targeted payments without penalties and also with state-dependent payments.

In terms of research methodology, this study employs both the economic analytical methods and quantitative methods from soil and hydrological engineering in the framework of integrated assessment models (IAMs) (Keiser, Kling and Shapiro 2018), combining the necessary modelling components to evaluate the emissions (nutrient and sediment), pollution sequestration (environmental services provided by riparian buffers), environmental and human outcomes (in terms of dynamics of payoffs and abatement costs, and pollutant reductions) and valuations.

Further, our results indicate that by using targeted PES that assigns higher compensations to buffers with higher environmental service performance levels, the buffer incentive program can be more effective in buffer installation and the consequential nutrient reductions. Also, riparian buffers take a long period of time (in our results about thirteen years) in order to fully develop and reach the maximum of environmental services provisions. Therefore, continuous policy support both in terms of monetary incentives that increase over time and technical assistance are necessary. The actual environmental services provided by riparian buffers may be affected by endogenous factors such as the specific vegetations in the buffers and capital and labor input in maintenance, as well as external random factor like soil conditions, weather, or hydrological conditions. Hence, future research may extend our results by incorporating these uncertainties in the dynamic model and evaluate how these variations may change the buffer adoptions and the environmental services provision.

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TABLES

Table 1. Annual Average Returns for Corn-Soybeans Rotation and Hay in Centre County, PA (U.S. Dollars per Acre) in 1999-2013

Year	Corn-Soybeans Rotation Returns	Hay Returns
1999	167.21	417.32
2000	146.61	209.44
2001	127.51	332.03
2002	16.84	600.09
2003	120.77	159.12
2004	190.74	385.74
2005	153.39	642.71
2006	14.96	693.25
2007	305.92	920.17
2008	241.38	540.69
2009	354.52	390.08
2010	105.43	701.92
2011	355.82	681.70
2012	270.28	662.89
2013	356.43	614.16

Table 2. Summary of the Land Uses in the Sample Region and the Buffer Designs

Land Use	**Total Land Parcel Size (acres)**
Corn-Soybeans Rotation	370.95
Hay	693.20
Non-agricultural	1,978.64
Water	124.76
Developed	942.29
Buffer Designs	**Widths and Vegetation Types**
Buffer 1	10 meters (32.8 feet) of grass
Buffer 2	15 meters (49.2 feet) of grass
Buffer 3	15 meters (49.2 feet) of trees
Buffer 4	6 meters (19.7 feet) of grass and 24 meters (78.7 feet) of trees
Buffer 5	30 meters (98.4 feet) of grass

Table 3. Annual PES Rates by Buffer Designs Using Targeted PES Compensation and the Uniform PES with Approximated CREP Payment Rates in Centre County, PA (U.S. Dollars per Pound)

Targeted PES						CREP Payment	
Year	Buffer 1	Buffer 2	Buffer 3	Buffer 4	Buffer 5	Year	Rate
1	384.66	408.74	341.37	385.11	431.41	1999	124.34
2	229.31	252.33	129.98	116.96	270.97	2000	120.20
3	170.95	233.98	146.35	187.22	266.48	2001	119.09
4	525.15	536.08	421.81	404.14	704.18	2002	119.06
5	1,385.29	1,497.97	1,463.04	1,402.44	1,422.50	2003	119.06
6	952.50	1,306.84	927.94	1,144.76	1,436.42	2004	196.01
7	533.23	642.71	607.32	530.55	735.41	2005	222.30
8	402.81	361.53	134.60	336.45	450.84	2006	230.44
9	217.15	296.19	247.28	238.13	280.46	2007	236.04
10	879.04	1,101.24	1,075.48	935.70	1,015.49	2008	251.87
11	375.56	421.57	301.56	414.21	505.37	2009	263.47
12	585.87	716.25	527.48	495.56	681.20	2010	278.61
13	1,468.47	1,788.90	1,611.27	2,018.22	2,079.50	2011	279.65
14	724.01	1,082.13	688.59	904.55	1,180.64	2012	288.47
15	615.08	740.44	566.50	583.05	714.21	2013	295.00

Table 4. Annual Average Abatement Costs and Reductions by Buffer Designs
4A. Baseline Results

	Buffer1	Buffer2	Buffer3	Buffer4	Buffer5
Base Year = 1999					
Abatement Costs	$97,599.97	$408,988.62	$303,887.68	$322,047.88	$180,234.93
Nitrogen (lbs.)	1,032.15	3,950.56	3,223.14	3,259.65	1,779.63
Phosphorus (lbs.)	303.85	1,318.26	918.75	969.77	547.72
Sediment (lbs.)	79,625.55	326,087.58	262,144.86	286,789.39	159,798.90
Base Year = 2013					
Abatement Costs	$253,399.48	$663,411.04	$368,331.83	$373,232.64	$541,996.84
Nitrogen (lbs.)	2,667.85	6,428.29	3,908.27	3,782.79	5,349.69
Phosphorus (lbs.)	791.56	2,135.10	1,112.43	1,122.18	1,655.82
Sediment (lbs.)	205,824.06	529,774.84	318,285.52	333,067.08	475,951.50

4B. Impose Penalty for Exit

	Buffer1	Buffer2	Buffer3	Buffer4	Buffer5
Base Year = 1999					
Abatement Costs	$35,155.12	$2,235.25	$85,030.88	$252,432.74	$57,378.17
Nitrogen (lbs.)	371.79	21.11	895.11	2,563.23	566.24
Phosphorus (lbs.)	109.53	7.22	258.73	757.11	174.27
Sediment (lbs.)	28,635.36	1,794.30	72,761.98	226,056.82	50,938.72
Base Year = 2013					
Abatement Costs	$89,074.98	$11,240.15	$125,434.79	$253,037.45	$196,535.45
Nitrogen (lbs.)	937.11	106.88	1,319.64	2,569.15	1,938.72
Phosphorus (lbs.)	278.20	36.25	382.07	759.00	599.98
Sediment (lbs.)	72,407.52	9,023.15	107,159.77	226,566.94	172,871.91

Table 5: Inputs to the DAG

Description	s_k	t_k	s_q	t_q	c_e	η_e	p_e	y_e	b_e
no buffer → no buffer	0	0	0	1	0	149	120.44	1.21	0.00
no buffer → grass buffer	0	0	1	1	122.67	149	120.44	1.21	139.49
no buffer → shrub buffer	0	0	2	1	190.53	149	120.44	1.21	185.45
no buffer → tree buffer	0	0	3	1	258.38	149	120.44	1.21	170.01
no buffer → no buffer	0	1	0	2	0	229	150.41	1.42	0.00
no buffer → grass buffer	0	1	1	2	122.67	229	150.41	1.42	139.49
no buffer → shrub buffer	0	1	2	2	190.53	229	150.41	1.42	219.20
no buffer → tree buffer	0	1	3	2	258.38	229	150.41	1.42	170.01
grass buffer → no buffer	1	1	0	2	0	229	150.41	1.42	0.00
grass buffer → grass buffer	1	1	1	2	0	229	150.41	1.42	151.89
grass buffer → shrub buffer	1	1	2	2	258.39	229	150.41	1.42	238.18
grass buffer → tree buffer	1	1	3	2	258.38	229	150.41	1.42	206.59
shrub buffer → no buffer	2	1	0	2	0	229	150.41	1.42	0.00
shrub buffer → shrub buffer	2	1	2	2	0	229	150.41	1.42	150.50
shrub buffer → tree buffer	2	1	3	2	0	229	150.41	1.42	215.97
tree buffer → tree buffer	3	1	3	2	258.38	229	150.41	1.42	252.55
no buffer → no buffer	0	2	0	3	0	332	266.63	1.37	0.00
no buffer → grass buffer	0	2	1	3	122.67	332	266.63	1.37	139.49
no buffer → shrub buffer	0	2	2	3	190.53	332	266.63	1.37	185.45
no buffer → tree buffer	0	2	3	3	258.38	332	266.63	1.37	170.01
grass buffer → no buffer	1	2	0	3	0	332	266.63	1.37	0.00
grass buffer → grass buffer	1	2	1	3	0	332	266.63	1.37	151.89
grass buffer → shrub buffer	1	2	2	3	258.38	332	266.63	1.37	238.18
grass buffer → tree buffer	1	2	3	3	258.38	332	266.63	1.37	265.13
shrub buffer → no buffer	2	2	0	3	0	332	266.63	1.37	0.00
shrub buffer → shrub buffer	2	2	2	3	0	332	266.63	1.37	138.76
shrub buffer → tree buffer	2	2	3	3	258.38	332	266.63	1.37	215.97
tree buffer → tree buffer	3	2	3	3	258.38	332	266.63	1.37	125.64

Note that the average size of agricultural parcels with riparian land in Centre County, PA $A = 160$ and the buffer size under consideration is 49.2 feet (15 meters) wide by 2613 feet (0.5 miles or 796.4 meters) long, which gives $z_{[(s_k,t_k),(s_q,t_q)]} = \begin{cases} 0 & \text{if } s_q = 0 \\ 0.01845 & \text{otherwise} \end{cases}$.

FIGURES

Figure 1. Spring Creek Watershed in Centre County, Pennsylvania

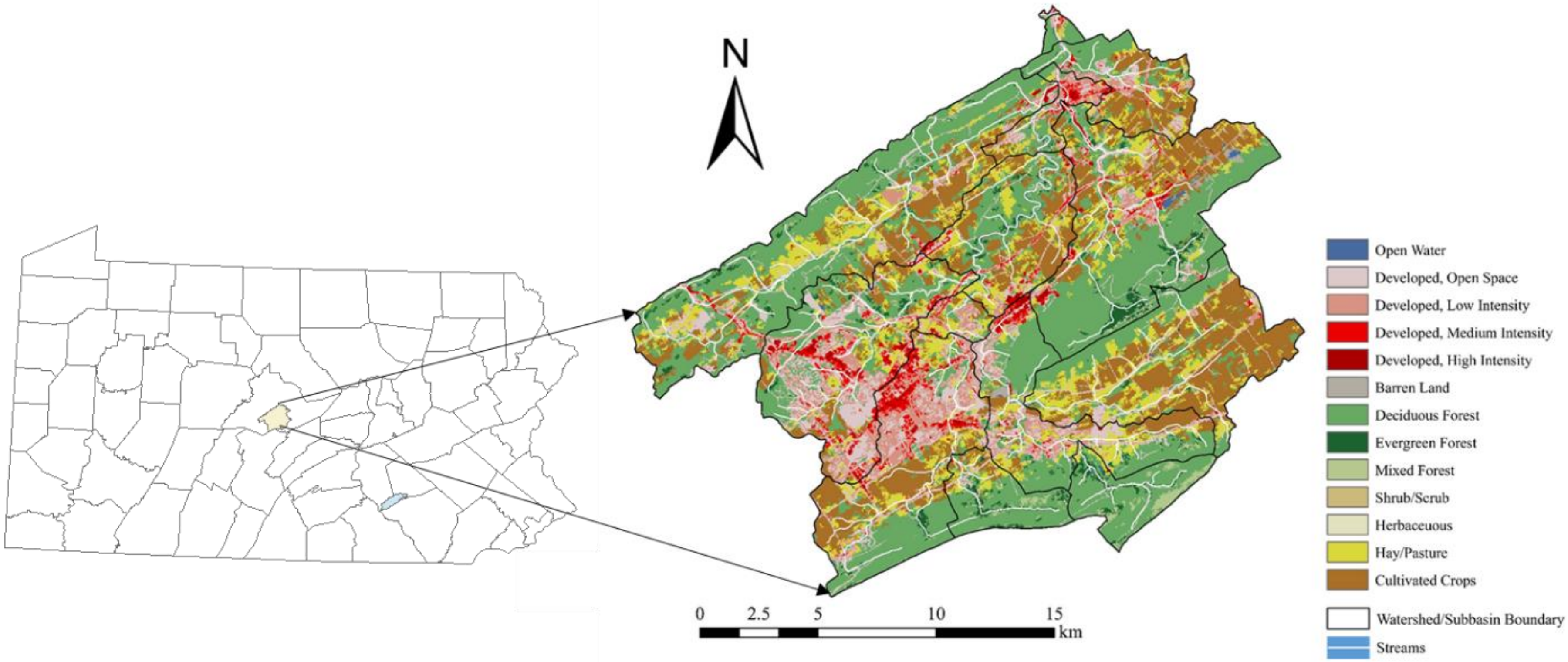
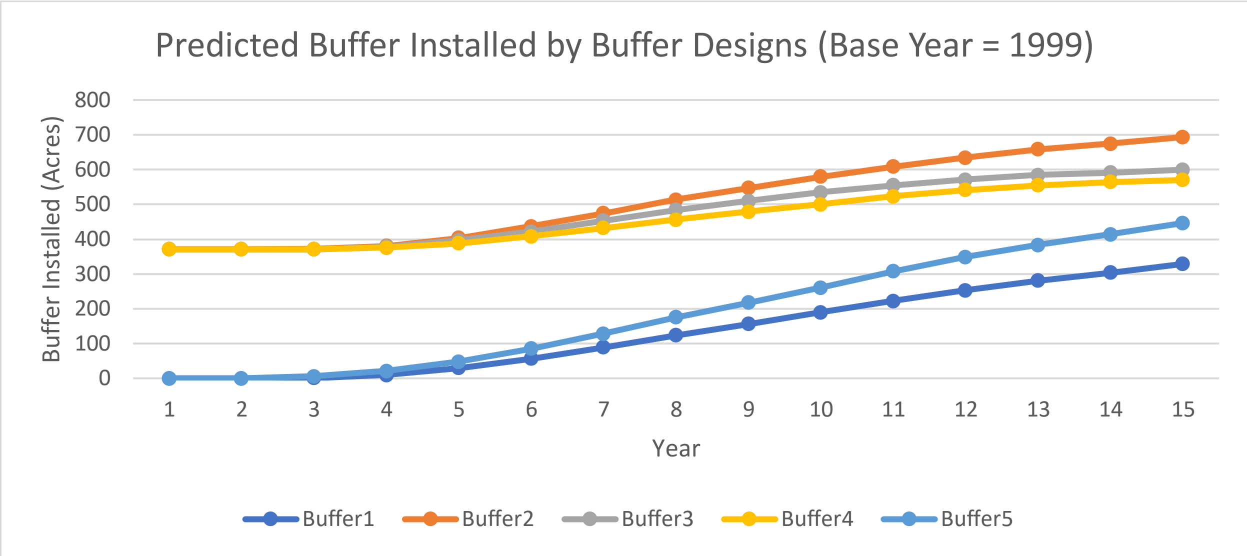


Figure 2. Predicted Buffer Installed in Fifteen Years Simulation



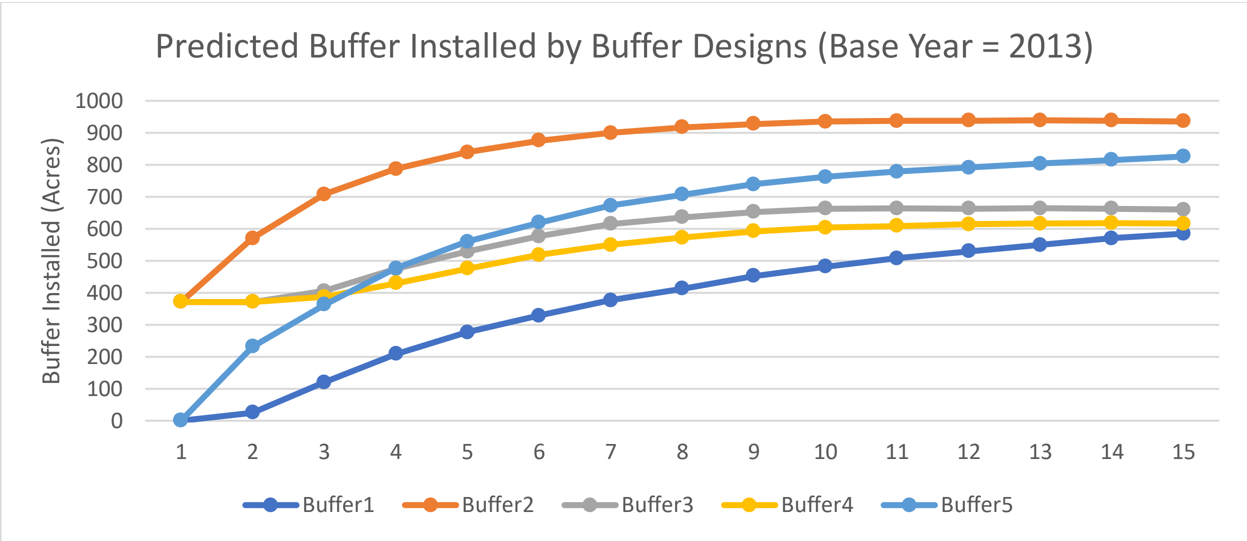
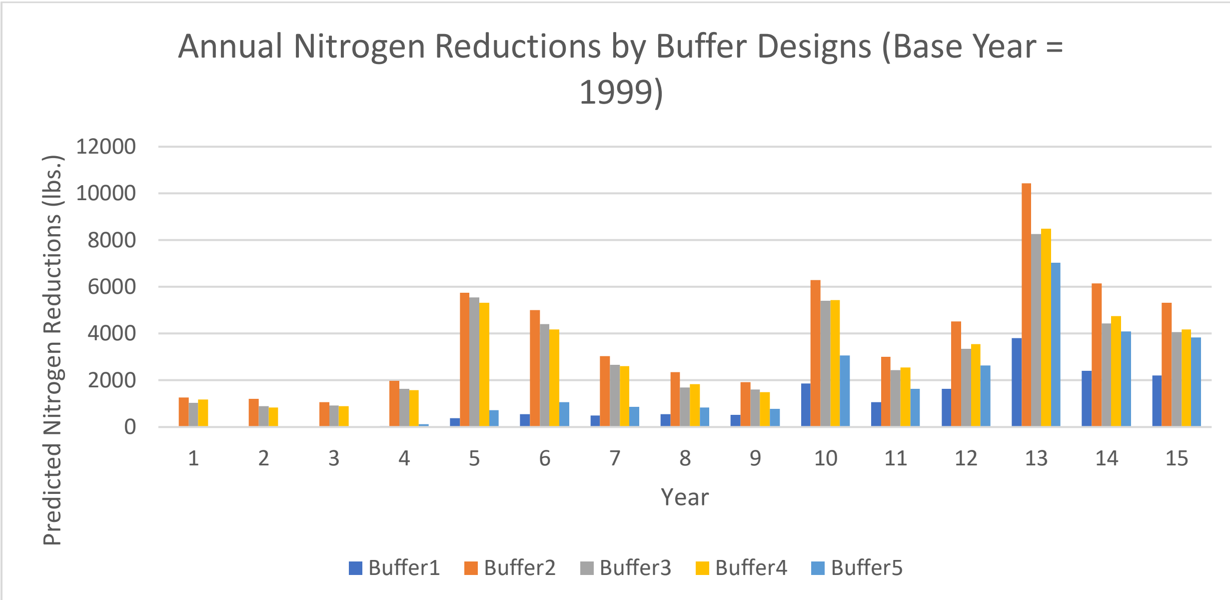


Figure 3. Predicted Nutrient Reductions by Buffer Designs



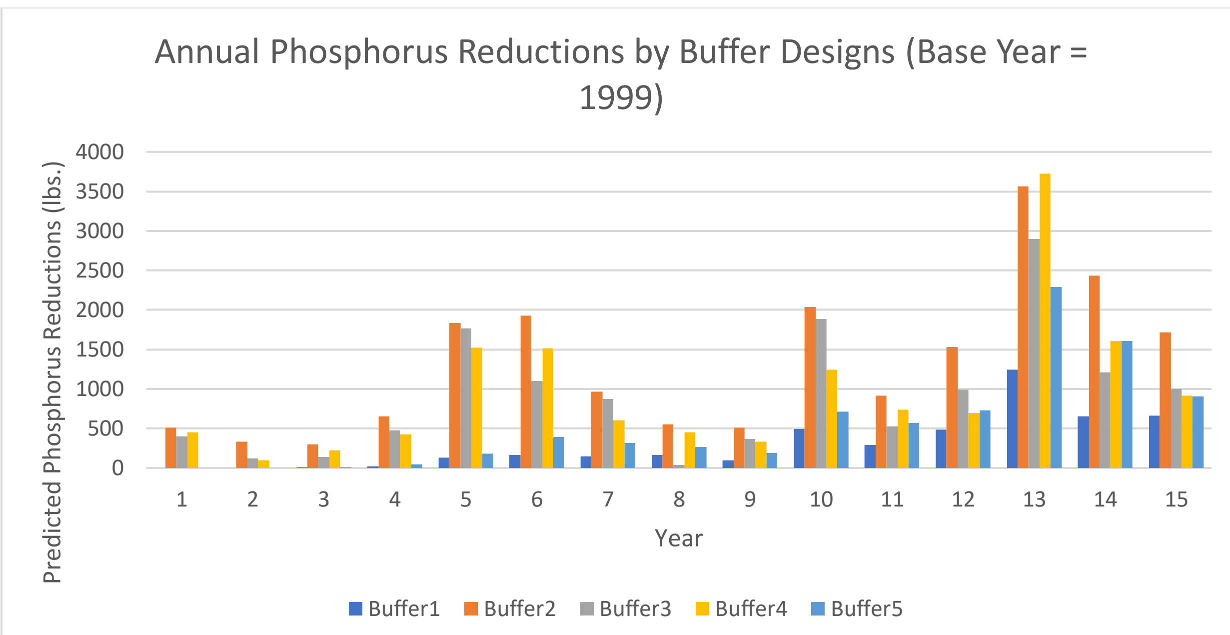
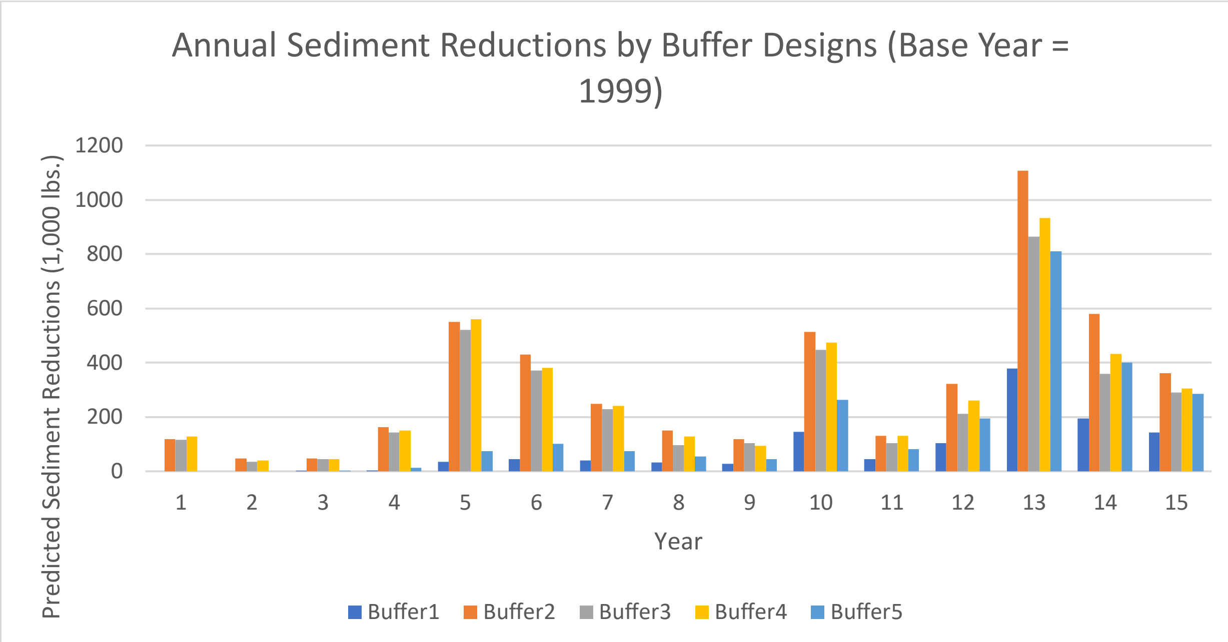


Figure 3. Continued



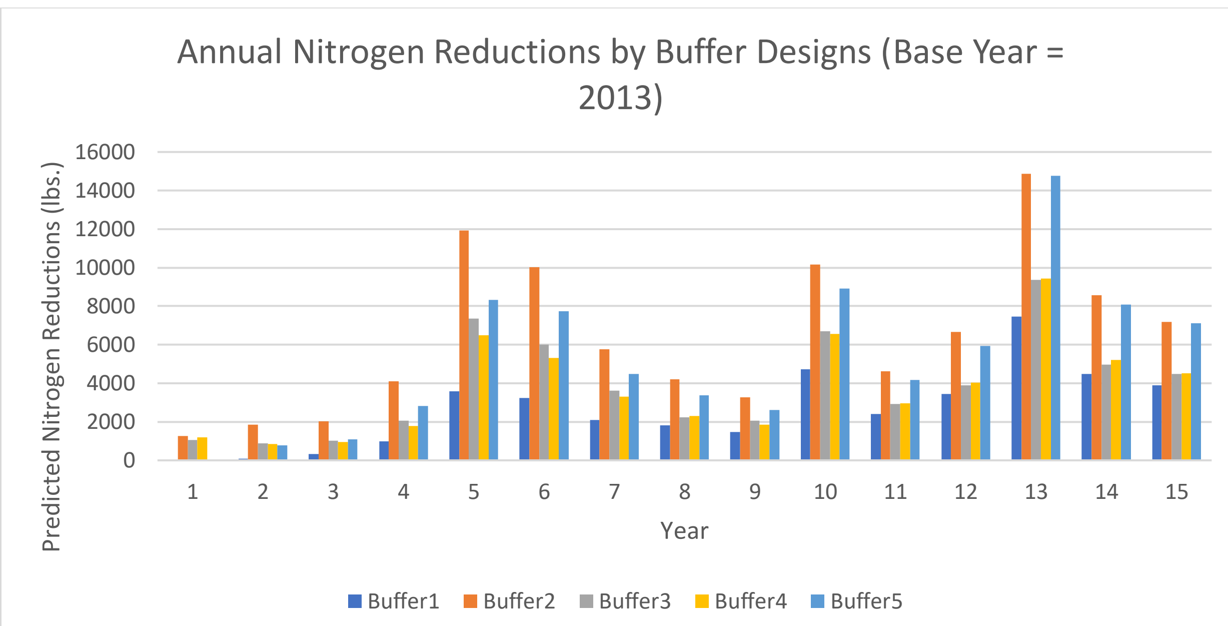
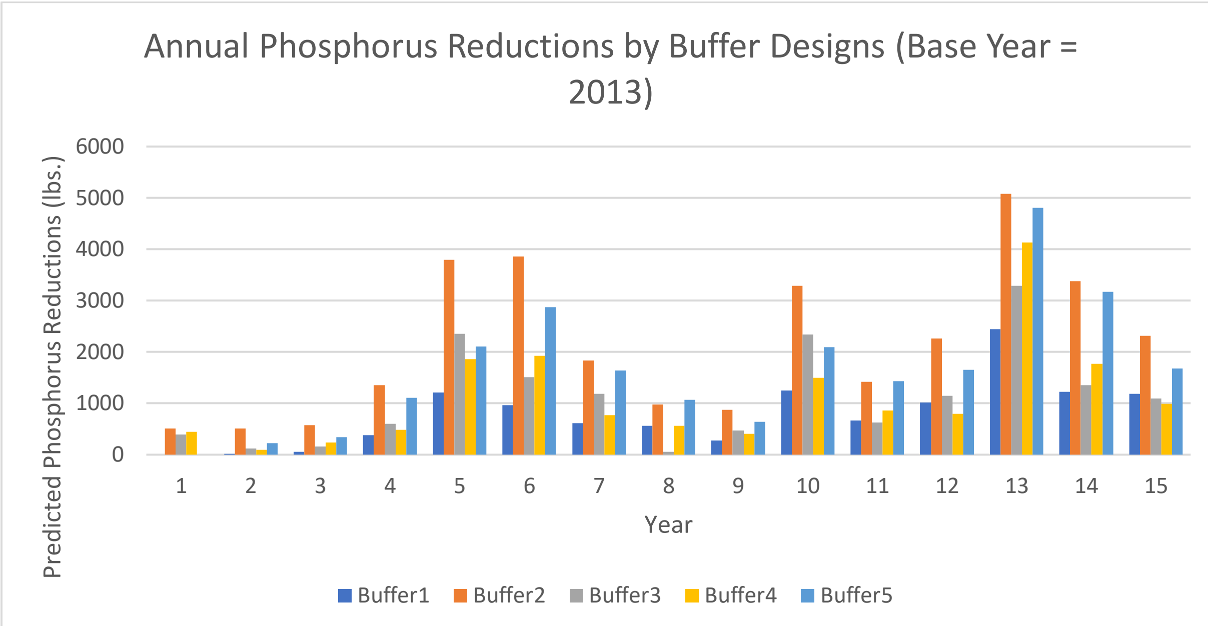


Figure 3. Continued



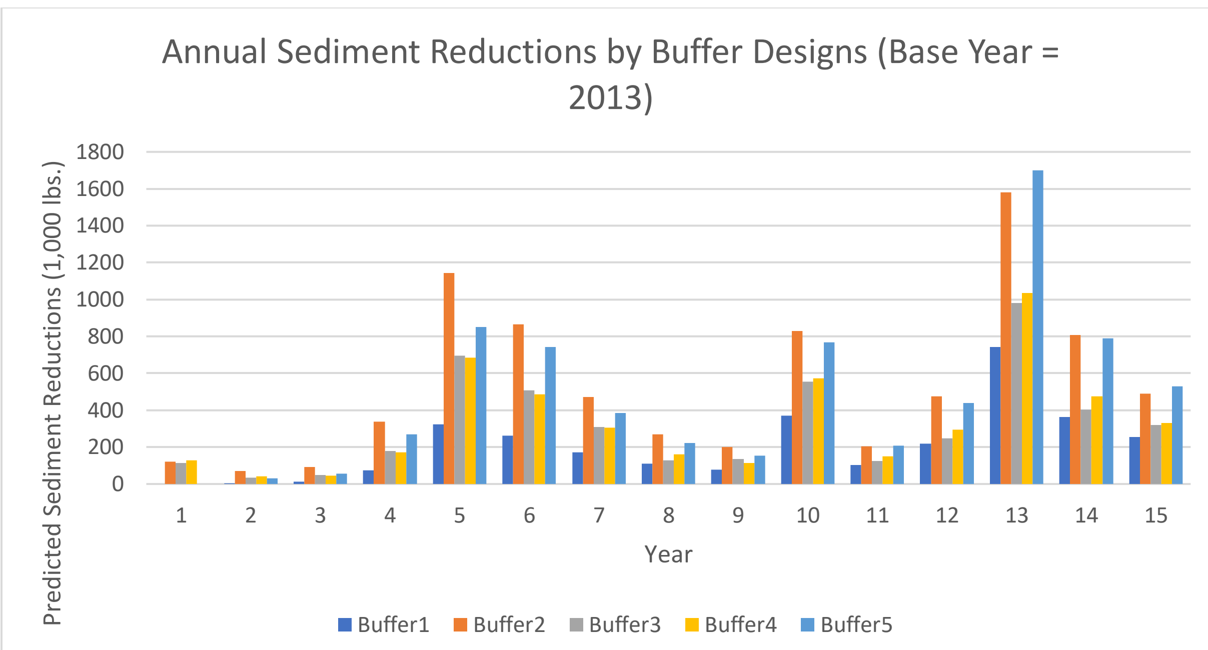
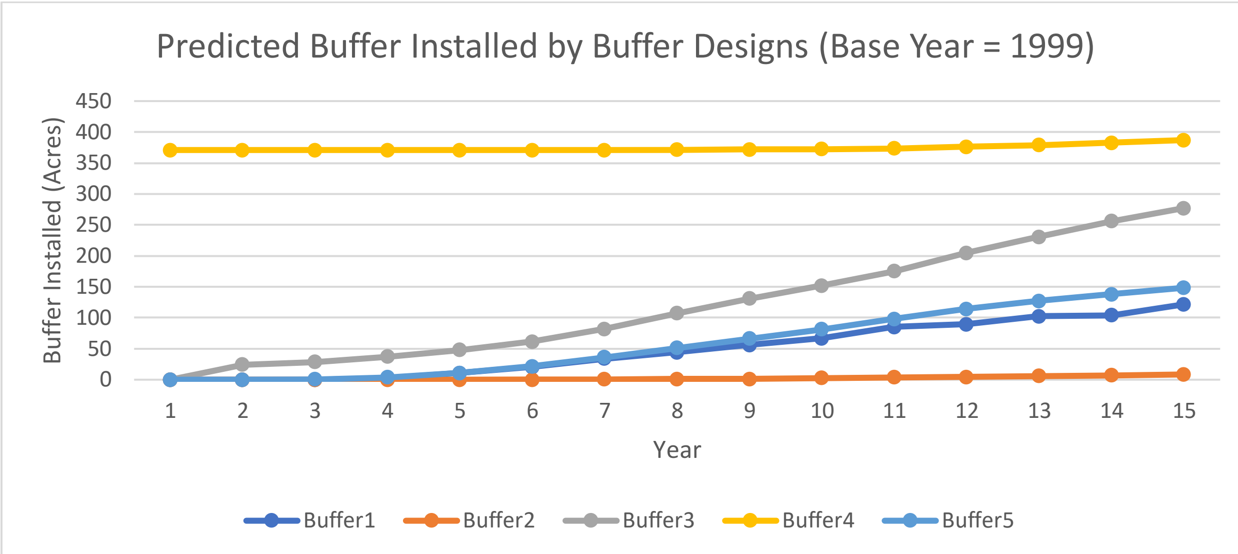


Figure 4. Predicted Buffer Installed in Fifteen Years Simulation with Penalty



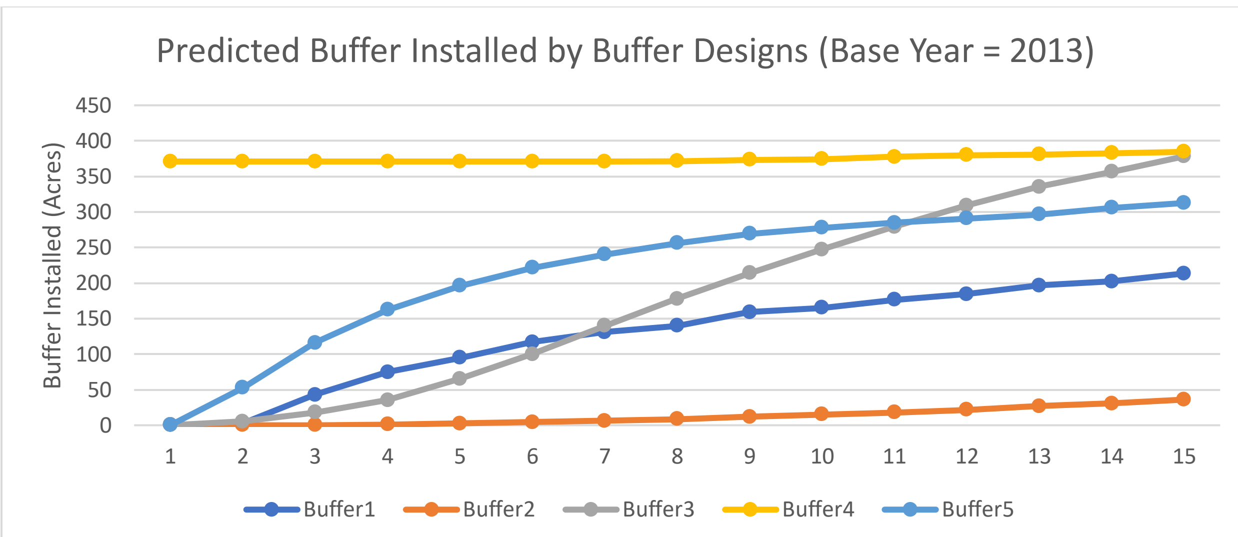
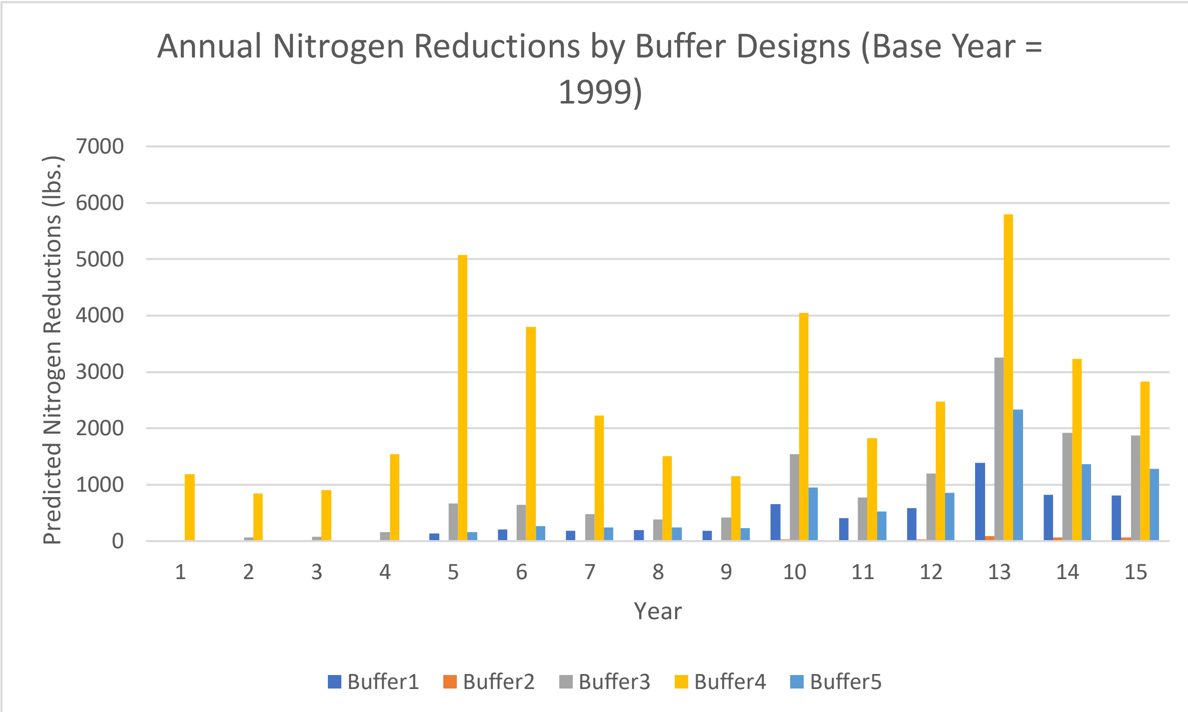


Figure 5. Predicted Nutrient Reductions by Buffer Designs with Penalty



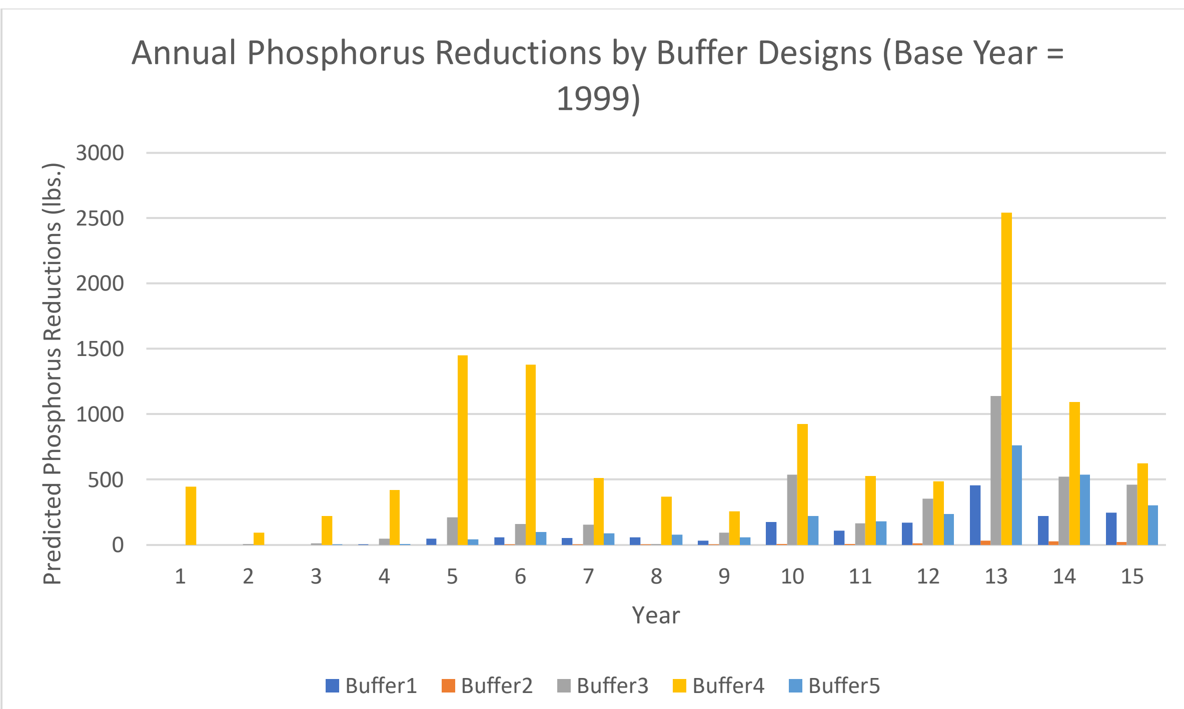
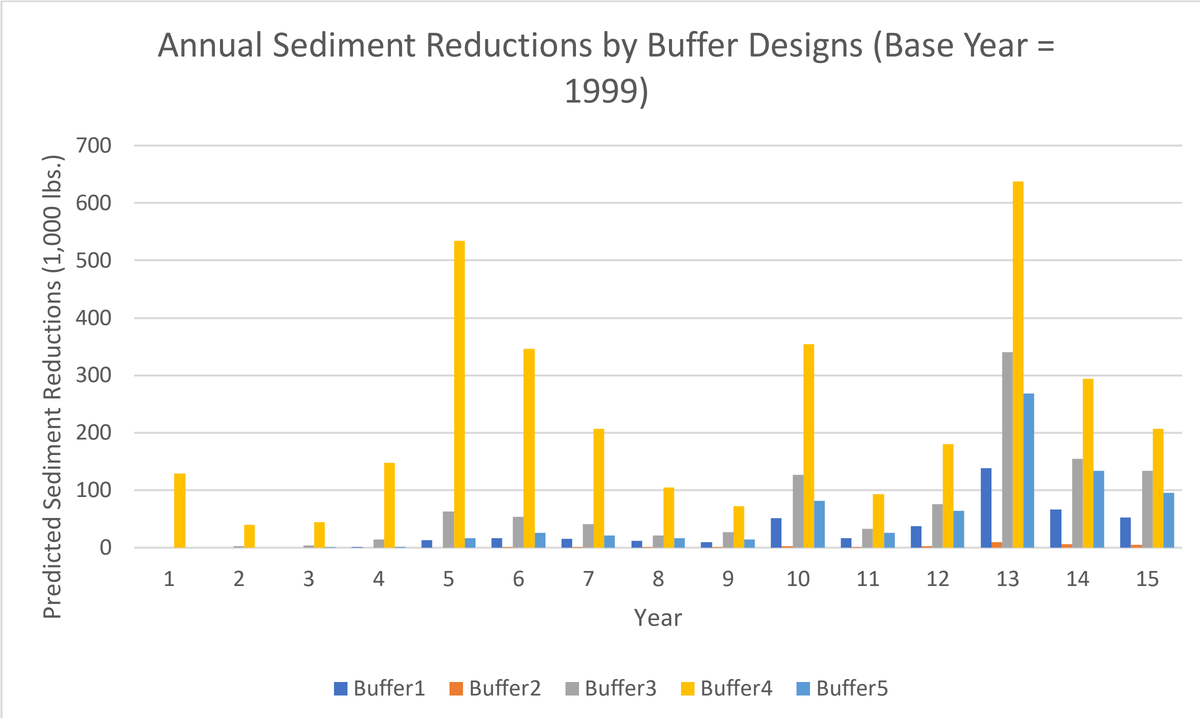


Figure 5. Continued



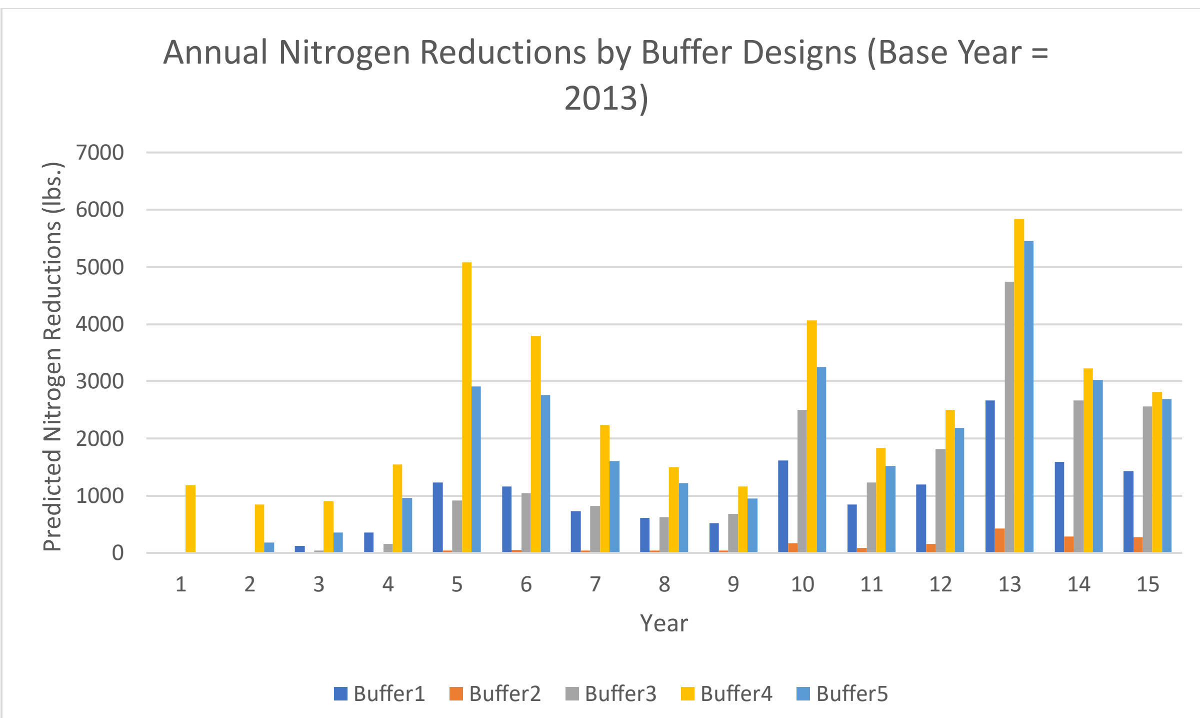
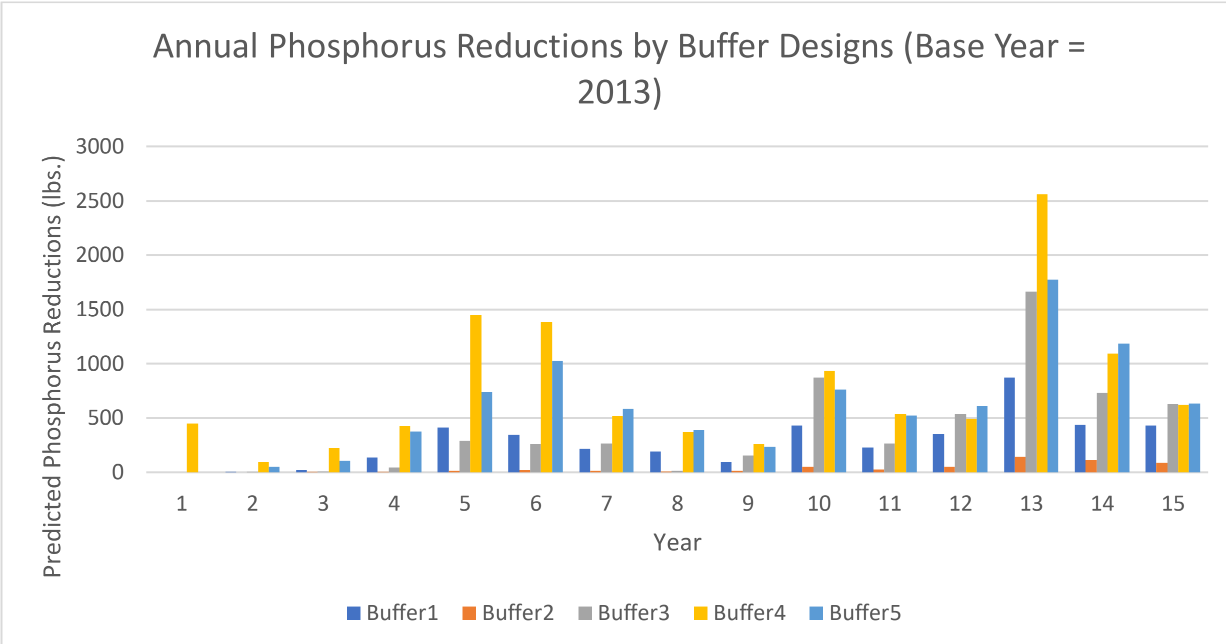


Figure 5. Continued



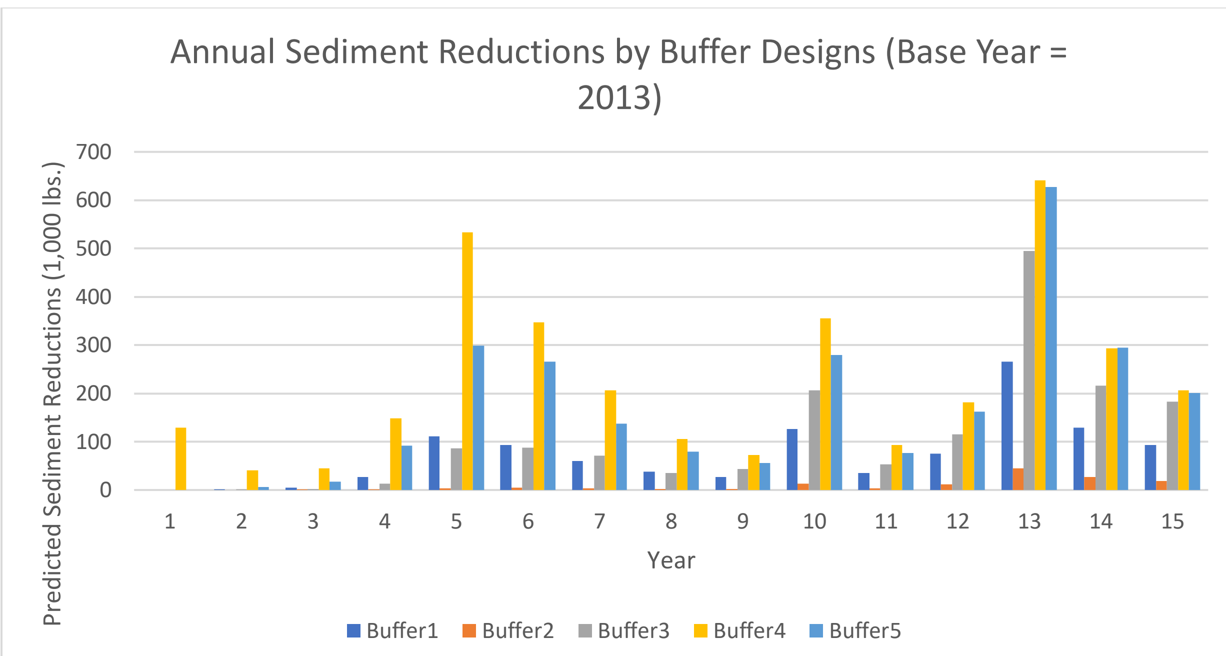
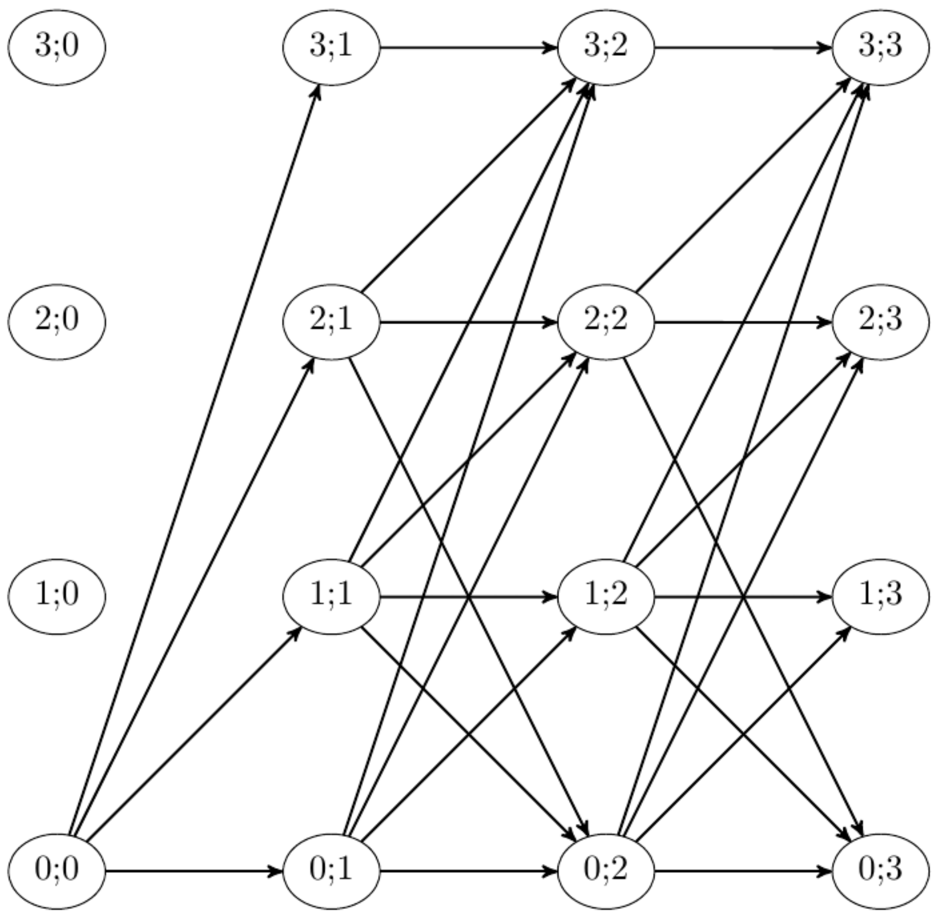
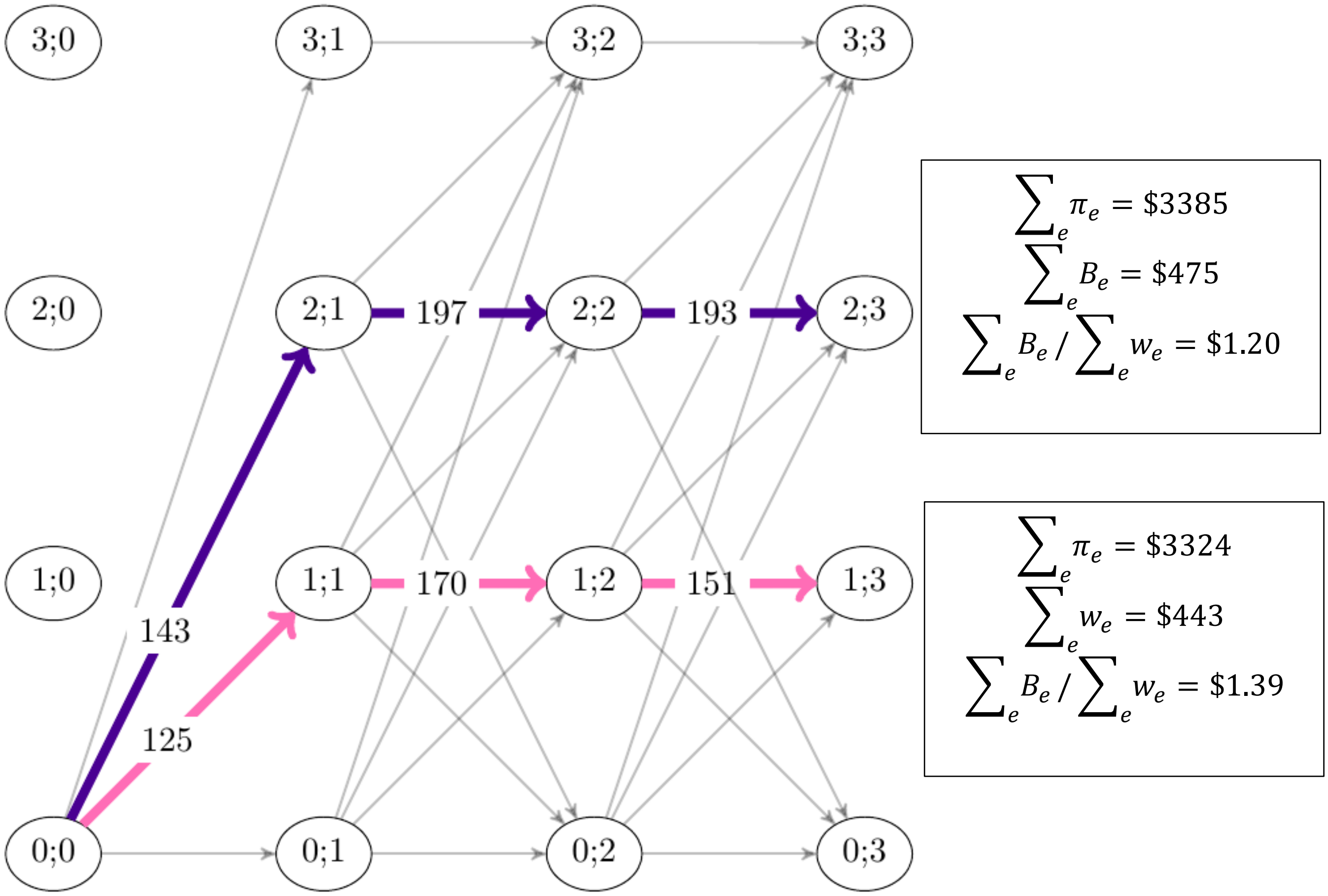


Figure 6: A DAG representation of farmers' profit maximization problem across riparian buffer designs and time periods



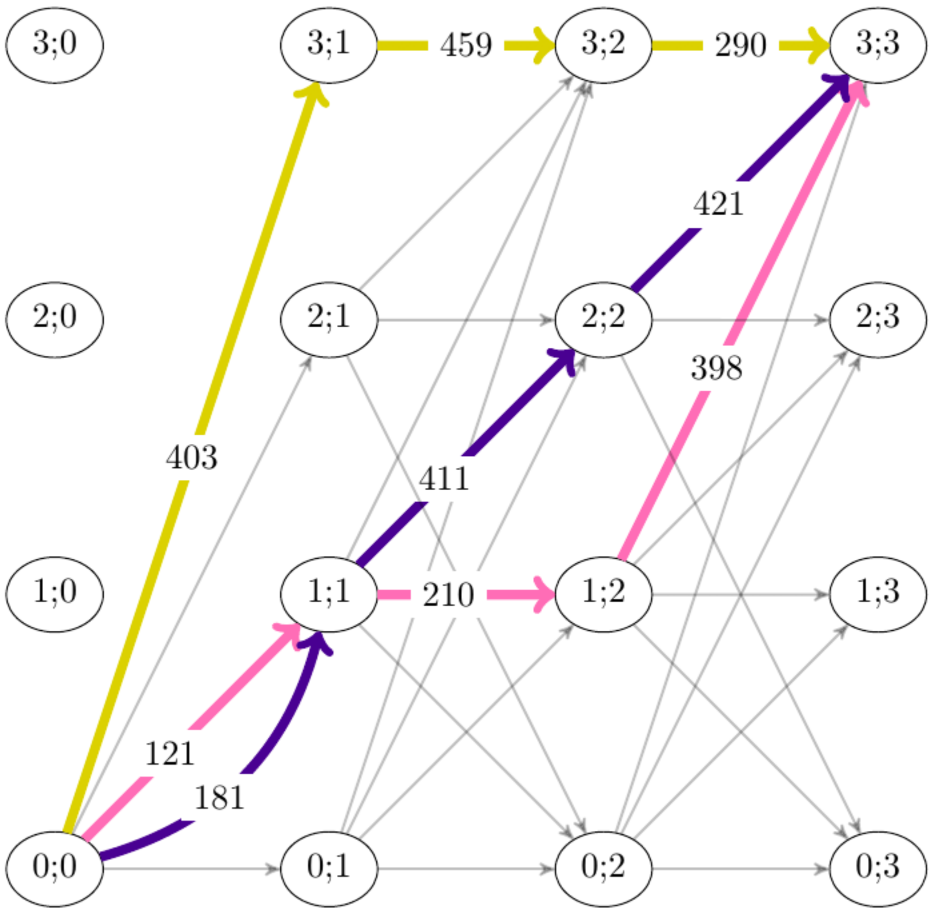
Note: Each vertex $v_k = (s_k, t_k)$ and each edge $e = \left[(s_k, t_k), \left(s_q, t_q\right)\right]$ is weighted by profits π_e and a corresponding water quality benefit b_e.

Figure 7: The maximum profit paths with the highest environmental benefits at the lowest costs with $w_{e,n} \sim Uniform(100,200)\ for\ n = (1, \dots, 9999)$



Note: The numbers on the edges represent the minimum PES payments $w_{e,n}$ in the simulation scenarios to achieve the selected path.

Figure 8: The maximum profit paths with the highest environmental benefits for a selection of paths that result in tree buffers (3,3) at the lowest costs with $w_{e,n} \sim Uniform(100{,}500)\ for\ n = (1, \ldots, 999999)$



Note: The numbers on the edges represent the minimum PES payments $w_{e,n}$ in the simulation scenarios to achieve the selected path.

APPENDIX A: NUTRIENT REDUCTION RATES BY BUFFER DESIGNS

Table A-1. Nutrient Reduction Rates for Five Buffer Designs (U.S. Pound per Acre)

Year		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Nitrogen	1	3.2	3.1	2.7	4.8	13.0	9.9	5.5	4.4	3.3	9.8	4.8	6.5	13.6	7.9	6.7
	2	3.4	3.3	2.8	5.2	14.2	11.4	6.4	4.6	3.5	10.9	4.9	7.1	15.8	9.1	7.7
	3	2.8	2.4	2.5	4.4	13.9	10.4	5.9	3.5	3.2	10.1	4.4	5.9	14.1	7.5	6.8
	4	3.2	2.3	2.4	4.2	13.7	10.2	6.0	4.0	3.1	10.9	4.9	6.6	15.3	8.4	7.3
	5	3.6	3.4	3.0	6.0	14.9	12.5	6.7	4.8	3.5	11.7	5.4	7.5	18.4	9.9	8.6
Phosphorus	1	1.3	0.8	0.5	1.8	4.4	2.9	1.6	1.4	0.6	2.6	1.3	1.9	4.5	2.2	2.0
	2	1.4	0.9	0.8	1.7	4.5	4.4	2.0	1.1	0.9	3.5	1.5	2.4	5.4	3.6	2.5
	3	1.1	0.3	0.4	1.3	4.5	2.6	1.9	0.1	0.7	3.5	1.0	1.7	5.0	2.0	1.7
	4	1.2	0.3	0.6	1.1	3.9	3.7	1.4	1.0	0.7	2.5	1.4	1.3	6.7	2.9	1.6
	5	1.4	1.0	0.9	2.3	3.8	4.6	2.4	1.5	0.9	2.8	1.8	2.1	6.0	3.9	2.0
Sediment*	1	0.3	0.1	0.1	0.4	1.2	0.8	0.5	0.3	0.2	0.8	0.2	0.4	1.4	0.6	0.4
	2	0.3	0.1	0.1	0.4	1.4	1.0	0.5	0.3	0.2	0.9	0.2	0.5	1.7	0.9	0.5
	3	0.3	0.1	0.1	0.4	1.3	0.9	0.5	0.2	0.2	0.8	0.2	0.4	1.5	0.6	0.5
	4	0.3	0.1	0.1	0.4	1.4	0.9	0.6	0.3	0.2	0.9	0.2	0.5	1.7	0.8	0.5
	5	0.4	0.1	0.2	0.6	1.5	1.2	0.6	0.3	0.2	1.0	0.3	0.6	2.1	1.0	0.6

*Note: Sediment is in 1,000s of U.S. Pounds per acre

APPENDIX B: GEOMETRIC BROWNIAN MOTION ESTIMATES

Using the data of annual returns to corn-soybeans rotation and hay, land use conversion costs and the annual targeted PES rates, we estimated GBM parameters $\{\hat{\alpha}_b, \hat{\sigma}_b, \hat{\alpha}_c, \hat{\sigma}_c, \hat{\alpha}_h, \hat{\sigma}_h, \hat{\rho}_{bc}, \hat{\rho}_{bh}\}$ for a total of ten groups of pairwise comparisons across the five buffer designs $b \in \{\text{Buffer 1}, \text{Buffer 2}, \text{Buffer 3}, \text{Buffer 4}, \text{Buffer 5}\}$ and the two agricultural land use alternatives $c, h \in \{\text{corn} - \text{soybeans rotation}, \text{hay}\}$. The estimated parameters are presented in Table B-1.

Table B-1. Maximum Likelihood Estimates of GBM Parameters

Parameters	Buffer 1	Buffer 2	Buffer 3	Buffer 4	Buffer 5
Buffer					
$\hat{\alpha}_b$	0.0547	0.0617	0.0711	0.0574	0.0541
$\hat{\sigma}_b$	0.2060	0.1963	0.2644	0.2357	0.1904
Corn-Soybeans Rotation					
$\hat{\alpha}_c$	0.1257	0.1257	0.1257	0.1257	0.1257
$\hat{\sigma}_c$	0.3784	0.3784	0.3784	0.3784	0.3784
$\hat{\rho}_{bc}$	-0.1032	0.007	0.3098	0.1236	-0.0191
Hay					
$\hat{\alpha}_h$	0.0404	0.0404	0.0404	0.0404	0.0404
$\hat{\sigma}_h$	0.1600	0.1600	0.1600	0.1600	0.1600
$\hat{\rho}_{bh}$	-0.2397	-0.2155	-0.1183	-0.1771	-0.1484

APPENDIX C: OPTIMAL SWITCHING BOUNDARY GRAPHS

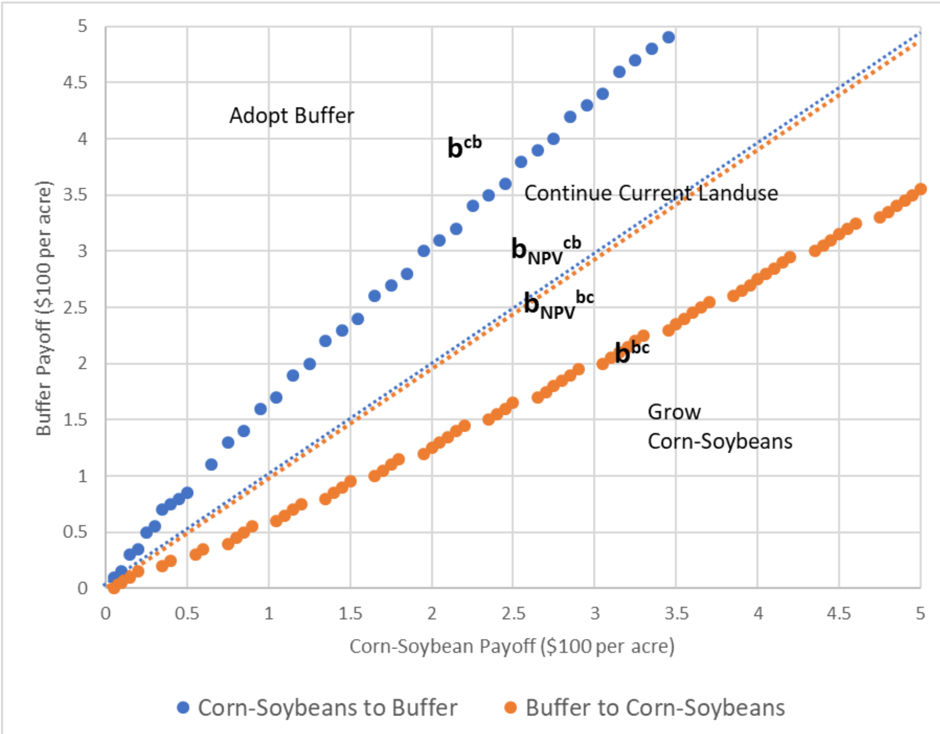
Figure C-1 presents the graphs of the optimal switching boundaries between agricultural land uses and buffers. Since the returns for buffers are essentially the PES that farmers and landowners receive for installing and maintaining buffers, these boundaries imply the necessary PES for farmers and landowners to adopt buffers given certain amounts of returns from agricultural land uses, or on the other hand given certain amounts of PES for farmers and landowners who currently have buffers the necessary returns from agricultural land uses to encourage them to opt out. To read the graphs, for example, in Figure C-1a, the optimal switching boundary for conversion from corn-soybeans to buffers with design of Buffer 1 is $b^{cb}(\cdot)$, and the optimal switching boundary for conversion from buffer to corn-soybeans is $b^{bc}(\cdot)$. The average return from corn-soybeans rotation in Centre County, PA in 2013 is \$356 per acre, and the corresponding targeted PES for Buffer 1 is \$615 per acre. Hence, for farmers and landowners whose land is currently used for corn-soybeans rotation, the necessary PES is approximately $b^{cb}(356) = \$510$ per acre in order to adopt grass buffer. Since the targeted PES for Buffer 1 is higher than $b^{cb}(356)$, the optimal land use decision for farmers whose land is used for corn-soybeans rotation in 2013 with returns equal to or less than \$356 per acre should be converting the agricultural land to buffers.

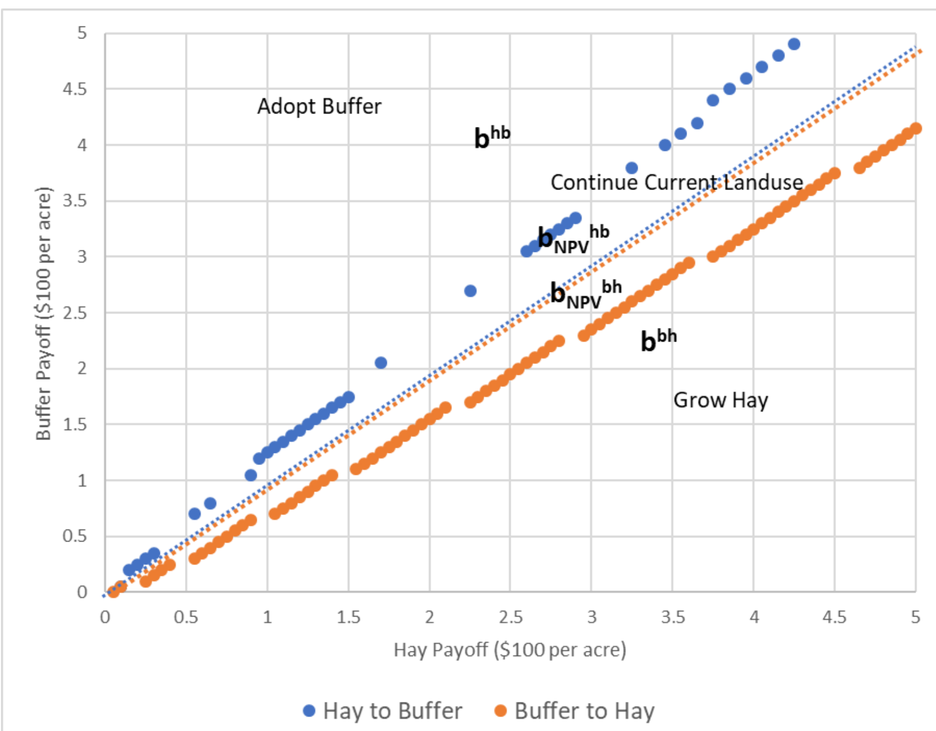
Table C-1 summarizes the necessary PES for farmers and landowners to adopt buffers given the average returns from agricultural land uses in Centre County, PA. Both 1999 and 2013 are used as base year. In the uniform PES scenario, buffers with any designs are paid equally at the same rate. Results show that both in 1999 and 2013 the necessary PES to incur conversions from agricultural land uses to buffers are higher than the uniform PES payments. Such results indicate that if farmers are only offered the uniform PES rates, then little to no conversion from agricultural land to buffers would happen. On the other hand, results suggest that with the targeted

PESs, agricultural land in corn-soybeans rotations would be converted to buffers for all five buffer designs both in 1999 and 2013. However, the necessary PES in order for agricultural land in hay production to be converted are higher than the targeted PESs, hence on average the hay land would not be converted to buffers.

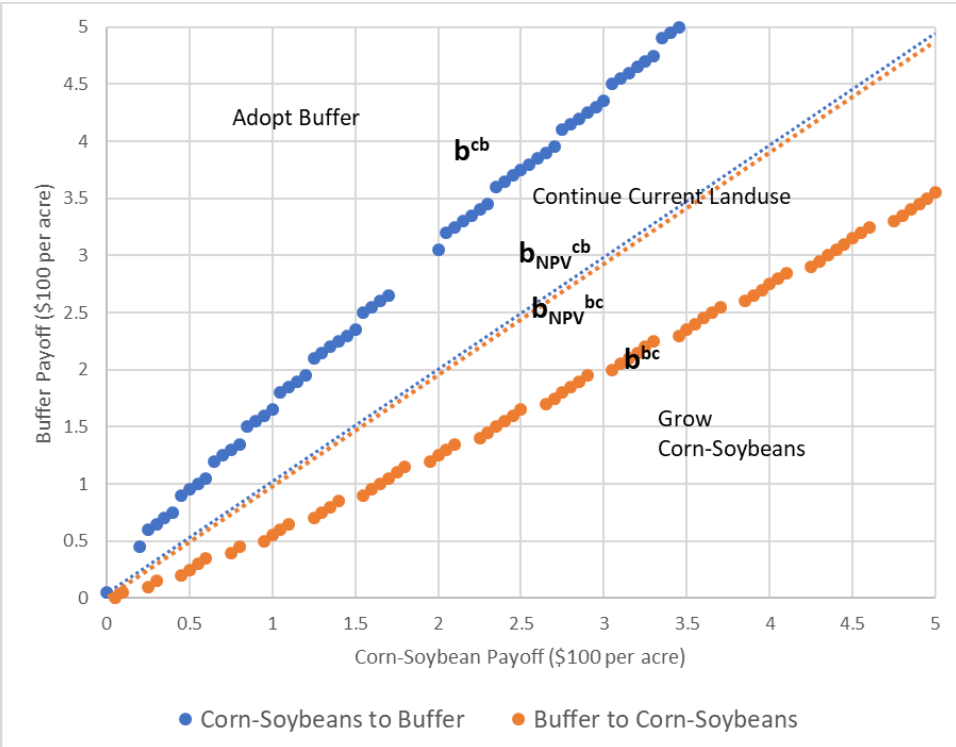
Figure C-1 Optimal Switching Boundaries between Agricultural Land Uses and Buffers

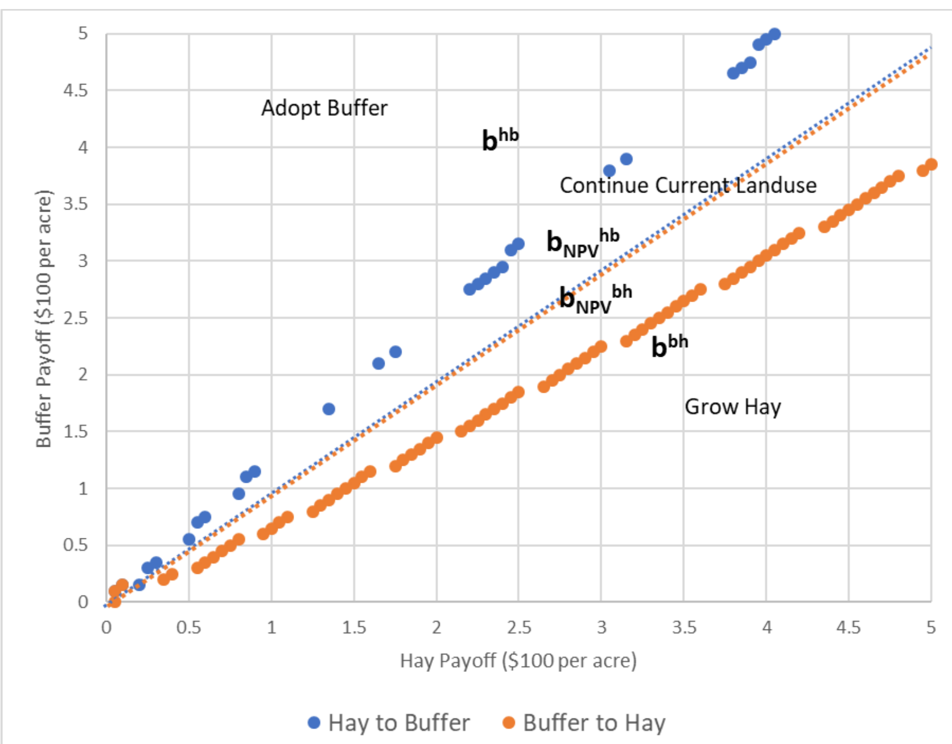
C-1a. Buffer Design 1



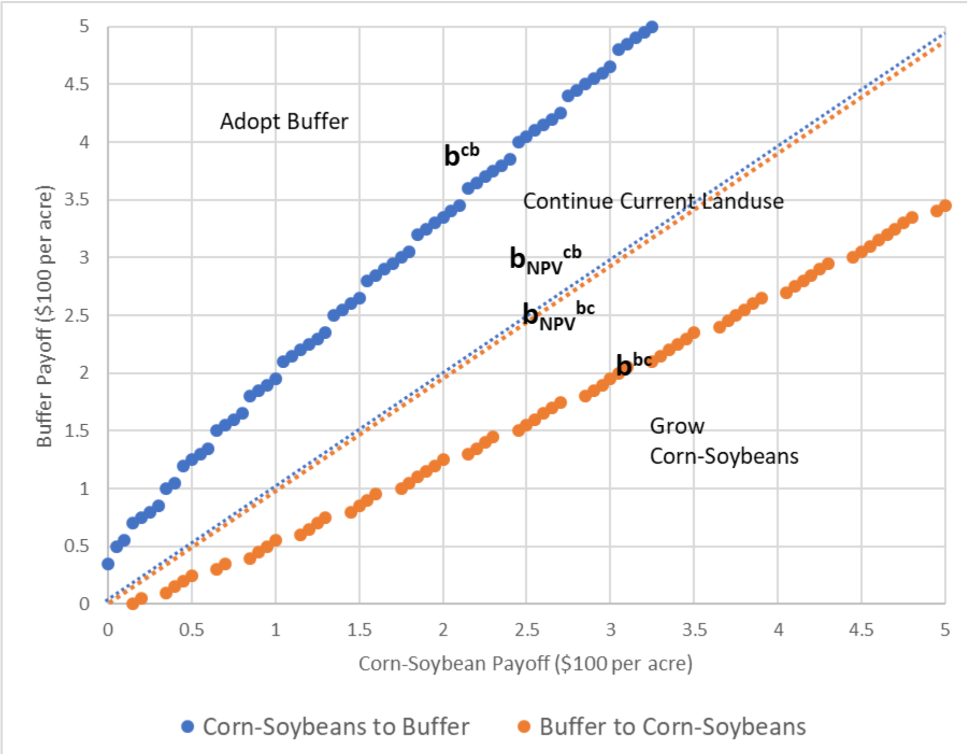


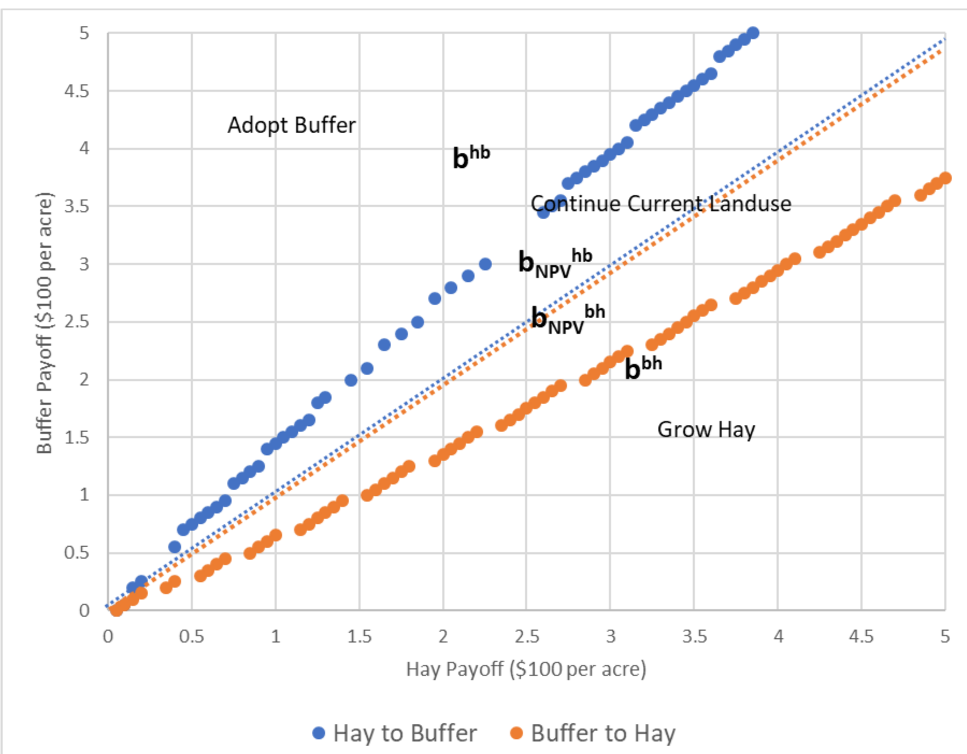
C-1b. Buffer Design 2



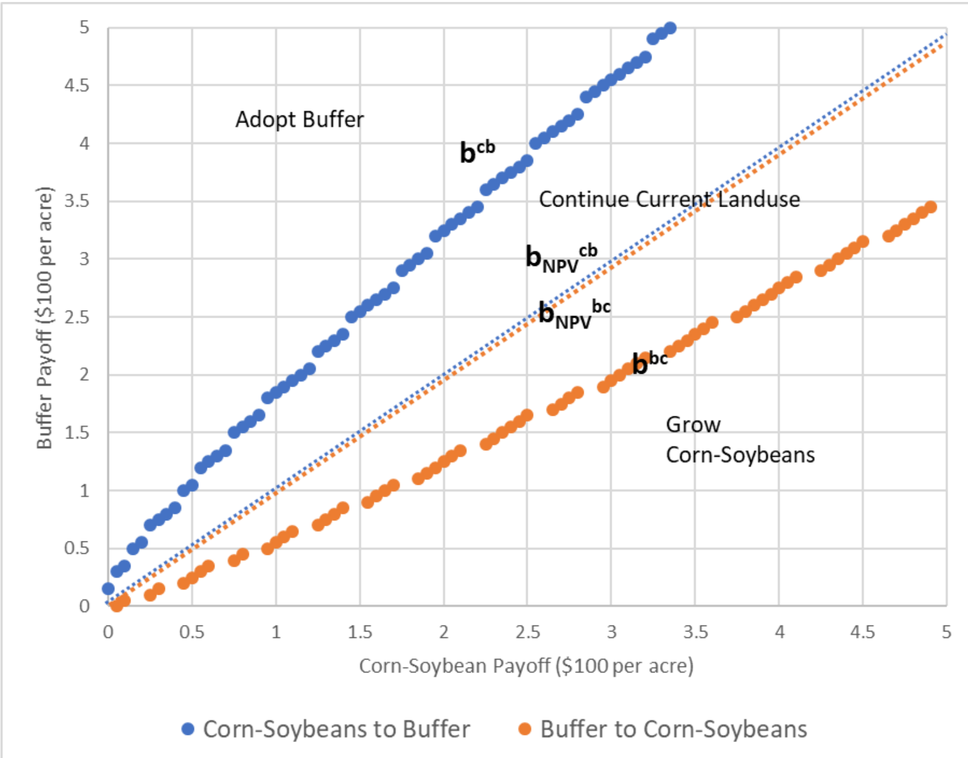


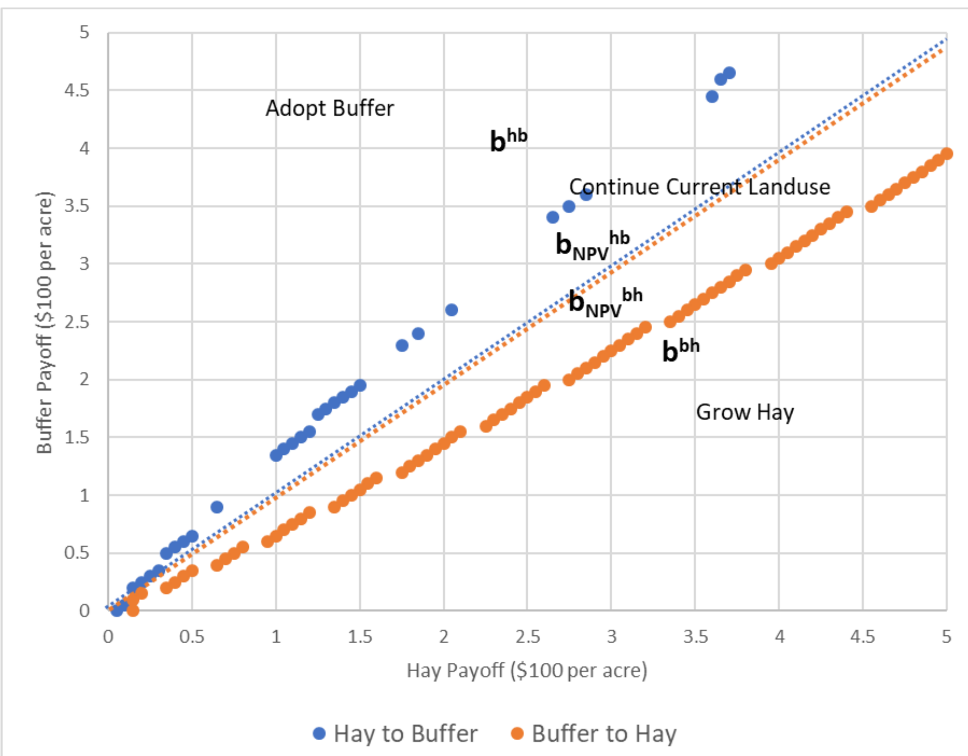
C-1c. Buffer Design 3



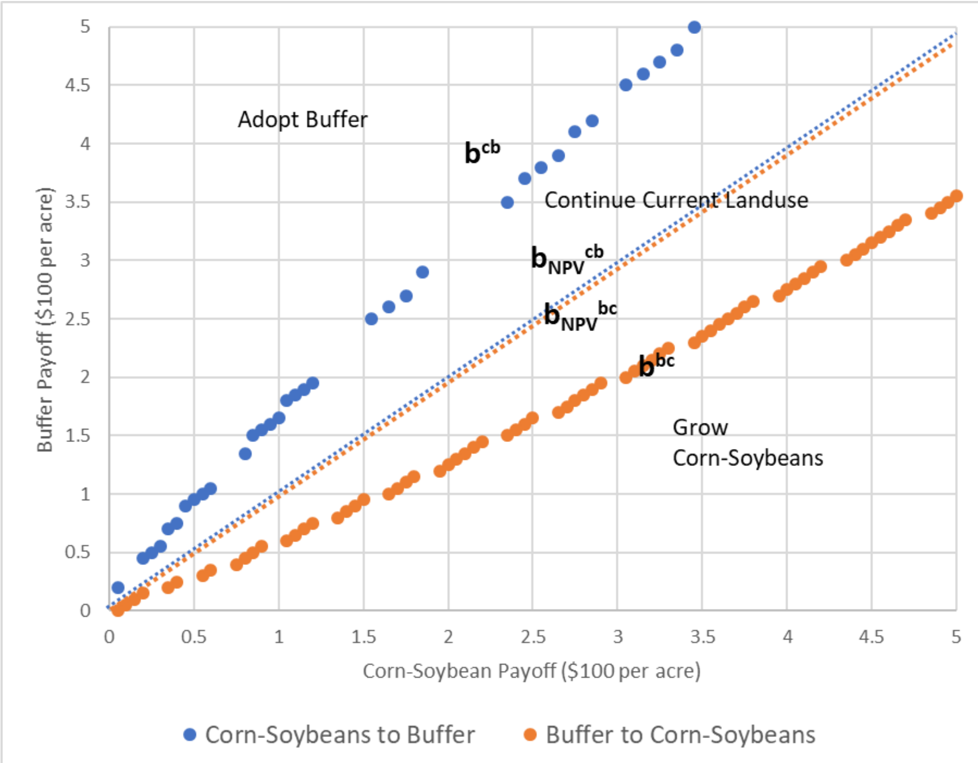


C-1d. Buffer Design 4





C-1e. Buffer Design 5



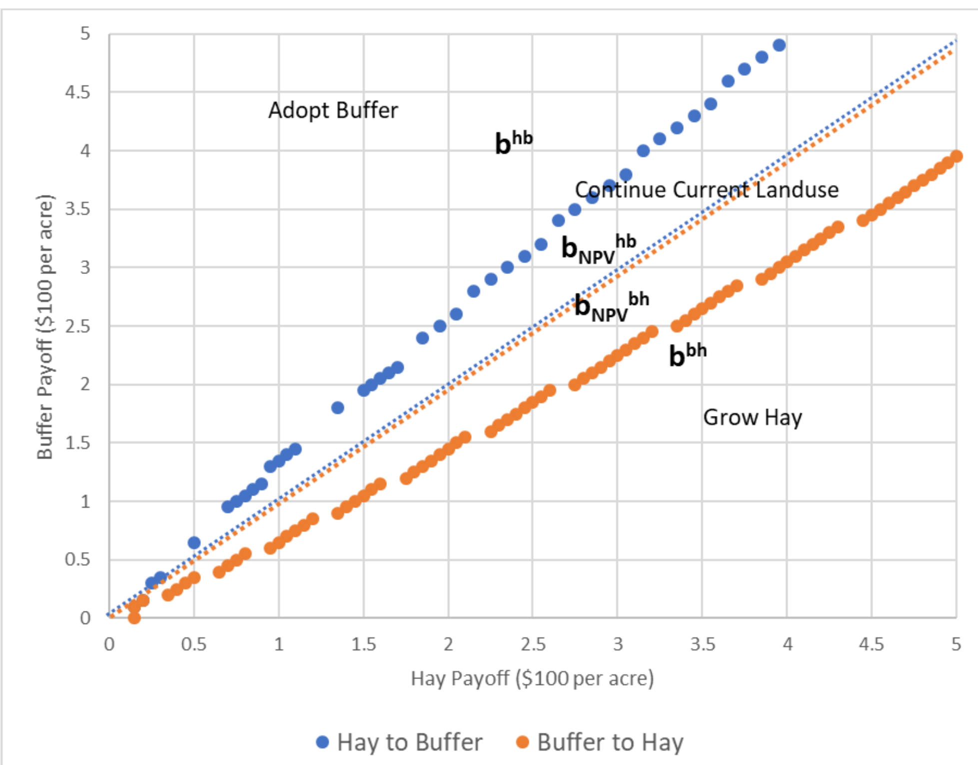


Table C-1. Dynamically Optimal Conversion Boundaries at the Average Payoffs from Agricultural Land Uses to Buffers in Centre County, PA (U.S. Dollars per Acre)

Necessary PES to Convert to Buffers	Payoff for Agricultural Land Use		Uniform PES
	Corn-Soybeans Rotation (1999 = 167.21; 2013 = 356.43)	Hay (1999 = 417.32; 2013 = 614.16)	
Base Year = 1999	560	590	124.34
Base Year = 2013	750	820	295.00

Table C-1. Continued

Base Year = 2013		Payoff for Agricultural Land Use: Corn-Soybeans Rotation (356.43)	Payoff for Agricultural Land Use: Hay (614.16)	Targeted PES Rate
Necessary PES to Convert to Buffers	Buffer 1	510	700	615.08
	Buffer 2	515	875	740.44
	Buffer 3	540	780	566.50
	Buffer 4	530	910	583.05
	Buffer 5	510	870	714.21

Base Year = 1999		Payoff for Agricultural Land Use: Corn-Soybeans Rotation (167.21)	Payoff for Agricultural Land Use: Hay (417.32)	Targeted PES Rate
Necessary PES to Convert to Buffers	Buffer 1	265	480	384.66
	Buffer 2	260	510	408.74
	Buffer 3	290	540	341.37
	Buffer 4	270	530	385.11
	Buffer 5	260	510	431.41