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Optimal Targeting of CREP to Improve Water Quality: Determining Land Rental Offers with Endogenous Sediment Deposition Coefficients

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Abstract

An integrated watershed management framework that combines detailed spatial biophysical attributes of land with a hydrologic model and an economic model is developed to study the cost-effective enrollment of land in the Conservation Reserve Enhancement Program (CREP). Compared with previous related studies that assumed exogenous sediment deposition coefficients related only to site specific characteristics, this research explicitly considers endogenous sediment deposition coefficients, that are determined by landuse decisions made by all land parcels in the run-off path, in determining land rental offers. The modeling framework is applied to one of the eligible watersheds, Court Creek, in Illinois. We find that the optimal targeting of land enrollment is much more cost-effective than a uniform land rental policy.

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Optimal Targeting of CREP to Improve Water Quality: Determining Land Rental Offers with Endogenous Sediment Deposition Coefficients

Growing concern about the adverse effects of agricultural activities on water quality has redirected the focus of soil conservation programs from reducing on-site erosion and maintaining soil productivity on fields towards reducing off-site damages to water bodies from sediment flows and nitrate run-off from fields. This shift in emphasis has led to the establishment of modified soil conservation programs that supplement the Conservation Reserve Program (CRP) by focusing on eligible land in narrowly defined zones and having numeric goals for environmental improvement.

The Illinois Conservation Reserve Enhancement Program (CREP) represents one of these new programs, initiated in 1998, to supplement the CRP and protect water quality in the Illinois River. It seeks to retiring environmentally sensitive cropland into grasses, trees and wetlands for at least 15 years and possibly for 30 years or permanently. Among the multiple objectives of the CREP are those of reducing sediment loading in the main stream of the Illinois River by 20 percent and nitrate loading by 10 percent. The CREP targets primarily cropland within the riparian buffer or 100-year floodplains of the rivers and streams in the Middle Illinois River Basin. Even within this zone of eligible land, there are 5.14 million acres of cropland, of which CREP seeks to retire only 0.23 million acres. There is thus a need for selectivity in the land to be enrolled in CREP. This would require information about land characteristics and their polluting potential at a detailed level as well as criteria to identify the land to be enrolled to achieve the desired environmental objectives at least cost.

A few studies have sought to develop criteria to identify the land that should be enrolled in the CRP. These include Ribaudo (1989) that analyzes alternative criteria for enrolling land to improve water quality given a fixed goal of the total amount of land to be enrolled. Babcock et al. (1996) examine the criteria to allocate a fixed budget to enroll land into a conservation program to maximize environmental benefits. These studies show that policy makers should purchase land with a high ratio of environmental benefits to enrollment costs measured in terms of dollars or acres enrolled. This can be achieved by prioritizing cropland according to their benefit cost ratio and then enrolling land selectively.

The implementation of such an approach is complicated for at least two reasons. First, the estimation of the potential environmental benefit of enrolling a land parcel is difficult because it depends not only on its own site-specific characteristics but also on the landuse decisions of parcels upstream and downstream from it. For example, the off-site damage to water quality due to erosion generated by a land parcel does not depend only on its own land-use choice and site-specific characteristics. It depends also on the availability of intervening land lying in the direction of the water flow and the sediment trapping efficiency (the portion of the sediment deposited on a land parcel and prevented from entering a water body) of these intervening land parcels. The trapping efficiency of a parcel depends on its own landuse decision and site-specific characteristics and on the amount of run-off flowing from upstream, which in turn depends on landuse decisions and site-specific characteristics of upstream parcels.

Second, even after the land to be enrolled has been identified, the implementation of that optimal enrollment plan in a decentralized decision making setting requires the provision of economic incentives to induce landowners to voluntarily retire their land. Hence there is a need to develop economic instruments that provide incentives for the landowners of the targeted cropland to retire their land. One such incentive-based instrument is a land rental payment scheme. With heterogeneity in site-specific characteristics and in the contribution of land parcels to off-site damages, these land rental offers need to differ across land parcels depending on their potential for sediment abatement if retired from crop production. Since the abatement potential of a land parcel is not exogenously determined but is dependent on landuse choices of upstream and downstream parcels which in turn are dependent on rental payment offers to those parcels, both rental payment offers and abatement potential need to be endogenously and simultaneously determined.

The first objective of this paper is to develop a methodology to identify the optimal enrollment of land in a watershed to achieve the pre-determined goals of reducing multiple pollutants, sediment and nitrate, at least cost. We develop an integrated watershed management framework that combines detailed spatial biophysical attributes of land using a GIS database with a hydrologic model that recognizes the inter-relationships between land parcels in determining their sediment trapping efficiency. The hydrologic and spatial characteristics of land are then incorporated into an economic model to identify cropland that would satisfy the CREP's sediment and nitrate reduction goals at least cost.

The second objective of the paper is to determine the optimal land-rental scheme required to achieve voluntary enrollment of the targeted land while accounting for interdependence between land parcels in their deposition ratios and abatement potential. We analyze how the per acre land rental offers vary with site-specific characteristics of land parcels. We then compare the cost-effectiveness of the optimal rental scheme with a land rental scheme that offers a uniform per acre rental offer for all parcels. The latter policy closely resembles the current policy approach for the implementation of the CREP that has fixed caps on per acre rental payments for land retirement offers in the eligible zone for each county based on typical cash rents in that county. Such a policy creates incentives for enrollment of land with low opportunity costs and not land with the highest environmental benefits-cost ratio unless costs and environmental benefits are highly negatively correlated. This framework is applied to one of the eligible watersheds, Court Creek, in Illinois, which is a pilot watershed for the CREP.

I. Previous Literature

The existing literature analyzing the optimal land enrollment decision in the CRP has relied on spatially aggregated data and analyzed the impact of the CRP either for a single representative farmer (Gillespie et al, 1990; Young, 1991; Johnson, 1993) or at a regional level (Ribaudo, 1989; Babcock et al., 1996; Kozloff, 1989). While the former studies ignore spatial issues and the impact of retirement on off-site water quality benefits, the latter studies rely primarily on the National Resource Inventory (NRI) and on the U.S. Geological Survey's National Stream Quality Accounting Network (NASQUAN) for data to determine those off-site benefits. The NRI determines the eligible cropland for the CRP using data for a few discrete points in each state in the U.S. while NASQUAN provides data on water quality at 470 monitoring stations in the U.S. As a result these studies are spatially too aggregated to allow precise targeting based on hydrologically determined impact on water quality. Ribaudo (1986, 1989) assumes a fixed sediment transport relationship based on soil characteristics while linking on-site erosion to off-site damages. Babcock et al. (1996) also construct an environmental damage index based on fixed site-specific characteristics and the universal soil loss equation which provides a measure of on-site erosion.

Several studies have incorporated detailed site-specific characteristics to analyze optimal changes in land management practices such as tillage or crop rotation and implications of fertilizer restrictions. Many of these have focused on the costs of reducing on-site erosion on fields in a watershed (Prato and Wu, 1991, 1996; Boggess et al., 1979; Seitz et al., 1979). Other studies have focused on reducing off-site damages due to sediment. These studies differ in their assumed linkages between on-site pollution generation and off-site damages, particularly for sediment. While many of them assume a fixed relationship between the two (see the survey in Braden et al., 1989; Carpentier et al., 1998), the study by Braden et al. recognizes that off-site damages are not proportional to on-site discharges, because the latter may be intercepted by intervening land parcels depending on the site-specific characteristics and management practices of those downstream parcels. This allows partial endogenization of the sediment deposition coefficients with the management practice choice of land parcels. However, Braden et al. do not incorporate the effect of the volume of pollution flowing into a land parcel from upstream on the capacity of that land parcel to intercept pollution. They also do not analyze alternative policy instruments that could be used to achieve land-use changes in a decentralized setting.

Lintner and Weersink (1999) developed a model that fully endogenizes the sediment deposition relationship while analyzing policies to control sediment bound emissions of nitrogen and phosphorus through changes in tillage and rotation practices. The present study expands the focus of landuse management models from a control of a single pollutant to multiple pollutants, namely, sediment and nitrate, and extends their framework to analyze the optimal targeting of discrete changes in landuse from cropland to permanent cover through enrollment in CREP.

II. Conceptual Framework

The framework developed here analyzes optimal land retirement decisions in a watershed to achieve a specified upper bound on the level of a pollutant. The watershed is divided into run-off channels, or flow paths, each denoted by $j=1,..J$, by which pollutants are transported from a land parcel to the water-body. Each flow path is divided into $i=1,..I_j$ land parcels of equal size, a, with parcel $i=1$ in each flow path being the closest to the water-body. Each flow path is well defined, unique, and independent of others and each land parcel is assumed to be homogeneous in terms of its site-specific characteristics. A land parcel is assumed to have a choice between two activities, denoted by k, where $k=0$ indicates retirement of land and $k=1$ indicates cropping of land. Suppose x_{ijk} is the land allocated to the k^{th} activity where 0£x_{ijk}£a with

(1) $$\sum_{k=0}^{1} x_{ijk} = a$$

Let p_{ij1} be the per acre quasi-rents earned through cropping on the i^{th} land parcel in the j^{th} channel and $p_{ij0} = 0$ be the per acre quasi-rents earned if this land parcel is retired from cropping and converted to permanent cover. Since we are focusing on land parcels that are currently under crop production, it is reasonable to assume that $p_{ij1}>0$. For simplicity, we assume here that each land parcel generates a single pollutant, sediment. The empirical model extends this to also include nitrate run-off generated by each land parcel. For activity k, the emissions per acre are denoted by e_{ijk}. The total amount of sediment produced by the i^{th} parcel is $\sum_{k=0}^{1} e_{ijk} x_{ijk}$.

A percentage $d_{i,i-m,j}$ of the sediment produced by the i^{th} parcel is deposited in each of the $i-m$ downstream parcels in flow path j, where $m=0,..i-1$. This is referred to as the deposition ratio of land parcel $i-m$ which depends on that parcel's site-specific characteristics $L_{i-m,j}$, landuse decision $x_{i-m,j,k}$ and amount of sediment $S_{i-m,j}$ flowing into that parcel. Thus,

(2) $d_{i,i-m,j} = d_{i,i-m,j}(L_{i-m,j}, x_{i-m,j,k}, S_{i-m,j})$ for $m=1,\ldots i-1$, where

(3) $S_{i-m,j} = S(L_{i-m+q}, x_{i-m+q,j,k})$ for $q=1,\ldots I_j-(i-m)$

The amount of sediment $S_{i-m,j}$ depends on the site-specific characteristics and landuse decisions by each of the q land parcels that are upstream from it. As $S_{i-m,j}$ increases, the deposition ratio $d_{i,i-m,j}$ is expected to decrease. The total amount of sediment S generated in the watershed that is loaded to the river is the sum of sediment loadings from the outlet of each run-off channel:

$$(4) \qquad S = \sum_{j=1}^{J} \sum_{i=1}^{I_j} (1 - \sum_{m=0}^{i-1} d_{i,i-m,j}) \sum_{k=0,1} e_{ijk} x_{ijk}$$

Suppose a social planner wants to maximize the total quasi-rent in the watershed, subject to (1) and a constraint on the maximum level of sediment, $\overline{S}$, that is loaded to the river. The Lagrangian of this optimization problem is represented as follows:

$$(5) \qquad L = \sum_{j=1}^{J} \sum_{i=1}^{I_j} p_{ij1} x_{ij1} + \sum_{j} \sum_{i} \mu_{ij} (a - \sum_{k=0,1} x_{ijk}) + l\, [\overline{S} - \sum_{j}^{J} \sum_{i}^{I_j} (1 - \sum_{m=0}^{i-1} d_{i,i-m,j}) \sum_{k=0,1} e_{ijk} x_{ijk}]]$$

The first order optimality condition is:

$$(6) \qquad \frac{\partial L}{\partial x_{ijk}} = \{ p_{ijk} - m_{ij} - l\, [(1 - \sum_{m=0}^{i-1} d_{i,i-m,j}) e_{ijk} - \sum_{m=0}^{i-1} \frac{\partial d_{i,i-m,j}}{\partial x_{ijk}} \sum_{k=0}^{1} e_{ijk} x_{ijk}] \leq 0 \text{ and } \frac{\partial L}{\partial x_{ijk}} x_{ijk} = 0, \forall\, i, j \text{ and } k,$$

where l represents the marginal cost of sediment abatement (dollars per ton of sediment) and the term in square brackets is the per acre contribution of the i^{th} parcel to off-site sediment (tons of sediment per acre). Since the sediment run-off from all flow paths contributes additively to the total sediment loading in the watershed, it is cost-effective to pay a uniform price per ton of sediment abatement in the watershed. The product of l and the term in square brackets is the cost of sediment abatement per acre while p_{ijk} represents the benefits per acre with crop production. The difference, m_{ij}, represents the net social benefit derived from the i^{th} land parcel. It is optimal to retire a land parcel from production, that is $x_{ij0}{*}{=}a$, only if the net social benefit from crop production are less than that can be obtained from land retirement. This is the case if:

$$(7) \qquad p_{ij1} - l\, [(1 - \sum_{m=1}^{i-1} d_{i,i-m,j}) e_{ij1} - \sum_{m=1}^{i-1} \frac{\partial d_{i,i-m,j}}{\partial x_{ij1}} e_{ij1} a\,] < -l\, [(1 - \sum_{m=1}^{i-1} d_{i,i-m,j}) e_{ij0} - \sum_{m=1}^{i-1} \frac{\partial d_{i,i-m,j}}{\partial x_{ij0}} e_{ij0} a\,] = m_{ij}$$

On the other hand, the social planner is indifferent between crop production and retirement of a land parcel if:

$$(8) \qquad p_{ij1} - l\, [(1 - \sum_{m=0}^{i-1} d_{i,i-m,j}) e_{ij1} - \sum_{m=0}^{i-1} \frac{\partial d_{i,i-m,j}}{\partial x_{ij1}} e_{ij1} a\,] = -l\, [(1 - \sum_{m=0}^{i-1} d_{i,i-m,j}) e_{ij0} - \sum_{m=0}^{i-1} \frac{\partial d_{i,i-m,j}}{\partial x_{ij0}} e_{ij0} a_{ij}\,] = m_{ij}$$

In this case the optimal share of land under each activity is indeterminate and $0 \le x_{ij1}^* \le a$. Condition (6) can be rearranged as follows to show that retirement of a land parcel from crop production is optimal if:

$$l\,[(1-\sum_{m=0}^{i-1} d_{i,i-m,j})(e_{ij1}-e_{ij0})+\sum_{m=0}^{i-1}\frac{\partial d_{i,i-m,j}}{\partial x_{ij0}}(e_{ij1}-e_{ij0})a\,] > p_{ij1}. \tag{9}$$

Since crop production is a more erosive activity, we have, $e_{ij1}>e_{ij0}$ and the difference $(e_{ij1}-e_{ij0})>0$ represents the on-site sediment abatement due to retirement of land from production. The term $(1-\sum_{m=0}^{i-1} d_{i,i-m,j})$ is also positive because we assume that more sediment cannot be loaded into the river than was generated on each of the land parcels. The product of these two terms [represented by the first term on the left-hand side of (9)] shows the off-site abatement of sediment generated on parcel *i* due to a change in its land use. It represents the direct contribution of land retirement by parcel *i* to off-site abatement of sediment. This term is large if the term $(1-\sum_{m=0}^{i-1} d_{i,i-m,j})$ is large and there are few or no downstream cells where the sediment generated by the i^{th} parcel can be deposited or if the deposition ratio of the downstream parcels is small.

The second term on the left hand side of (9) is also positive because the term $\frac{\partial d_{i,i-m,j}}{\partial x_{ij0}}>0$. This term shows the indirect impact of land-use decisions by (upstream) parcel *i* on sediment deposition ratios downstream in a channel. This is because an increase in the share of the i^{th} land parcel that is retired reduces on-site erosion and volume of sediment flow to downstream parcels, thereby increasing the deposition ratio of each of the *i-m* cells. The land-use decision of parcel *i* reduces off-site sediment loadings by increasing the abatement potential of downstream cells.

Together the terms on the left hand side of (9) indicates that a land parcel should retire from cropping activities either if it is close to the water-body and land retirement would have a large negative effect on its erosion generation or if it is an upstream cell but its land retirement decision would lead to a large improvement in the trapping efficiency of the downstream cells. Additionally, land retirement is optimal if the forgone quasi-rent from crop production is low.

The analysis above also shows the fallacy of focusing only on retiring land in parcels with high on-site erosion. If we focused only on reducing on-site erosion then land parcels where (e_{ij1}-e_{ij0}) is large should be retired from crop production. This would ignore the other terms on the left hand side in (9) which depend on the location of the land parcel in a flow path and on its impact on the deposition ratios of other parcels.

The minimum per acre payment a landowner would be willing to accept to retire the i^{th} parcel is p_{ij1}. The maximum per acre payment the government would be willing to offer to induce retirement of the land is given by the expression on the left-hand side of (9) which represents the marginal social cost of crop production on that parcel. To the extent that there is a strict inequality in (9), the maximum payment that the social planner is willing to offer per acre of land enrolled would generate a surplus for the landowner that is enrolling his land in a conservation program. As can be seen, this maximum payment is a function of the contribution of a land parcel to off-site sediment abatement. This contribution consists of two parts, first being the amount of off-site damages due to on-site erosion generated that are reduced and second being the improvement in trapping efficiency it causes in the downstream cells by retiring from crop production. Therefore while the rental payment per ton of abatement is uniform across land parcels, the rental offer per acre needs to vary across parcels depending on their direct contribution to abatement and also on their indirect contribution in the form of an externality benefit to other parcels by increasing their trapping efficiency.

III. Empirical Model

To empirically apply the conceptual model developed above, the entire watershed is partitioned into small management units that are grouped into run-off channels for sediment flow from upland areas to the river. The land parcels eligible for enrollment in CREP are restricted to those in the riparian buffer, defined here by the first three land parcels adjacent to the river in each flow path or run-off channel. The flow of run-off in any three-parcel channel is independent of that in adjacent channels. However, the deposition ratios for the parcels within a flow channel are dependent on landuse decisions and site-specific characteristics of upstream parcels. We assume that each land parcel will be either fully cropped or fully retired from production.

Typically this type of 'either/or' problems are formulated as mixed integer (binary) programming problems. However, the large number of land parcels (if the land parcels are to be sufficiently small to be homogenous entities in terms of their economic profitability and individual contribution to environmental pollution) in a typical watershed, the non-linear relationships between on-site erosion and off-site sediment loading, and the need to simultaneously determine the enrollment decision for each parcel and its endogenous deposition ratio would lead to a very large scale nonlinear integer programming model, which would be very difficult (if not impossible) to solve numerically.

We therefore develop an empirical model that involves transforming the above problem into one with exogenously specified relationships between on-site erosion generation and off-site sediment loading for each flow channel as explained below. This is used to obtain optimal landuse patterns in the watershed to achieve given environmental constraints. We then use the optimal land-use decisions to obtain the deposition ratios for each land parcel while recognizing the interdependence between these ratios among land parcels in each flow channel. Following that we determine each land parcels contribution to abatement of sediment/nitrate loading in the watershed and the optimal per acre rental payment offers to individual parcels to achieve the optimal land use.

The first step of determining the optimal land-use in the watershed is achieved as follows. Instead of defining a binary decision variable (i.e., enroll or not) for each parcel individually, we generate all possible combinations of enrollment decisions by land parcels in a flow channel. This leads to at most 8 (=2^3) different combinations of enrollment decisions that can be made for a 3-parcel channel[1]. We denote these 8 alternative land-use plans for each channel of parcels by $p=1,\ldots,8$ where $p=1$ corresponds to the *CCC* plan. The total profits with crop production for each channel, $j=1,\ldots J$, under each of the land-use plans is the sum of the profits for each parcel and is denoted by R_{pj}. Let E_{pj} and N_{pj} denote the total

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[1] These combinations are GGG, GGC, GCG, GCC, CGG, CCG, CGC, and CCC where C denotes crop production and G denotes enrollment in a land retirement program that requires the planting of permanent grass cover.

sediment and nitrate generated, respectively, by channel j under plan p. Let $(1- d_{pj})$ and $(1- q_{pj})$ denote the fractions of that sediment and nitrate that is loaded into the waterbody. Each d_{pj} and q_{pj} is exogenously fixed and represents the deposition ratio of a channel under land use plan p. The choice between alternative plans is determined by introducing $0 \le z_{pj}$£1, an endogenous convex combination (weight) variable associated with the enrollment plan p for channel j with $\sum_{p=1}^{8} z_{pj} = 1$. The ceilings on the maximum levels of sediment and nitrates that can be loaded into the water-body by the watershed are represented by $\overline{S}$ and $\overline{N}$ respectively. The algebraic model that determines the optimum enrollment option for all J flow paths is as follows:

(10) $$Maximize \ \sum_{j=1}^{J} \sum_{p=1}^{8} R_{pj} \, z_{pj} \text{ subject to}$$

(11) $$\sum_{j=1}^{J} \sum_{p=1}^{8} (1 - d_{pj}) E_{pj} \, z_{pj} \le \overline{S}$$

(12) $$\sum_{j=1}^{J} \sum_{p=1}^{8} (1 - q_{pj}) N_{pj} \, z_{pj} \le \overline{N}$$

(13) $$\sum_{p=1}^{8} z_{pj} = 1 \text{ for all } j=1,..J$$

(14) $$z_{pj} \text{ ³ } 0 \text{ for all } p, j$$

Note that the endogenous weight variables, z_{pj}, are defined as continuous variables, and from (13) and (14) they can take any arbitrary value in the range of $[0,1]$. This means that for each channel the model solution can have a weighted sum of alternative enrollment plans for each channel, with the endogenous weights adding up to 1. However, in any feasible solution all z_{pj} but one, have to take binary values, either 0 or 1. This can be seen as follows: The number of variables and constraints in the above model are $8J$ and $J+2$, respectively. Therefore, any basic feasible solution can have at most $J+2$ positive variables. Equation (14) implies that there is at least one positive variable for each channel, otherwise the sum cannot be equal to 1. These nonzero variables determine J of the $J+2$ basic variables, one variable belonging to each channel, and leaves only two remaining basic variables which may belong to a channel associated with any of the J channels. Thus, except for these two channels, for all other channels we must have $z_{pj} =1$ for some option p and z_{pj} =0 for all other options. Moreover, for those two channels we can have either two nonzero z_{pj}'s in each channel or three nonzero z_{pj}'s in one channel and only one nonzero z_{pj} in the other channel. Binary solutions for the enrollment choice variables for all channels imply that the model may select one of the p plans for flow path j rather than a mixed enrollment option. Therefore, after rounding the non-binary solution for that single channel to a binary solution, we obtain a pure binary optimum solution which very closely approximates the true binary solution of the enrollment problem that would be obtained from an integer programming formulation (where z_{pj}'s would be defined as binary variables). The error involved in this approach is negligibly small, but the convenience of this approximation procedure is enormous. First, linear programming allows us to solve the model regardless of its dimensions (i.e., the number of channels and enrollment plans). Second, a shadow price interpretation of the optimum solution, which is important for determining economic policy incentives as will be elaborated below, is now possible, unlike in the case of an integer programming formulation.

The shadow prices s and r associated with constraints (11) and (12) represent the marginal cost of sediment and nitrate abatement to the constrained levels. It can be shown[2] that the term $s[(1-d_{pj})E_{pj}-(1-d_{1j})E_{1j}]+r[(1-q_{pj})N_{pj}-(1-q_{1j})N_{1j}]$ for $p=2,..8$, represents the maximum payment that the social planner would be willing to offer flow path j for choosing the land use option $p>1$ and enrolling at least one parcel rather than choosing the CCC option. This payment would be sufficient to induce flow path j to choose plan p.

The solution to this model provides the optimum shadow price information to determine an appropriate price incentive, a uniform price s per unit of sediment abatement and r per unit of nitrate abatement, that can be offered to each flow channel to choose plan p. To distribute the total payment among individual parcels contained in each flow channel, we need to disaggregate the contribution of each parcel to the total abatement achieved by the flow channel. The procedure used to do so is explained here by using a specific example to estimate the contribution of each land parcel to sediment abatement. Suppose for instance that the plan GGC is found to be optimal for a particular flow channel. This means

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[2] Proof of this is a straightforward matter and requires standard linear programming theory and optimality conditions. Therefore, it is not explained in detail here, but available upon request.

that the first two parcels adjacent to the river should be targeted for enrollment and the third parcel (farthest from the river) should not be targeted. The total abatement can be allocated to the three parcels by considering the sediment/nitrate loading that would have been achieved under the GGC, CGC and CCC options. For example, in the case of sediment loading, let S_{1j} be the sediment loading under plan $p=1$ (that is, CCC) and S_{2j} be the sediment loading achieved by switching to the CGC plan. The difference between the two can be interpreted as the sediment abatement achieved by the land retirement decision of the middle parcel alone. Then, the payment for that parcel for sediment abatement must be $s(S_{1j}-S_{2j})$. If S_{3j} is the sediment loading under the GGC plan, then $S_{2j}-S_{3j}$ is the sediment abatement contribution of the first parcel (adjacent to the river), and therefore the payment for that cell must be $s(S_{2j}-S_{3j})$. Note that since $s(S_{1j}-S_{2j})+ s(S_{2j}-S_{3j})=s(S_{1j}-S_{3j})$ corresponds to the total payment made to the channel j, the sum of payments for individual parcels equals the total payment for the entire 3-parcel channel. Similarly, the contribution of each land parcel's land use decision to nitrate abatement by each channel and the rental payment to be offered to it can be determined.

IV. Data

The 67,717 acre Court Creek watershed located in Knox county, Illinois was selected for our empirical application. Typical of the watersheds within CREP, Court Creek is a highly productive agricultural watershed with nutrient- and sediment-impaired waters. Cropland comprises 46 percent; grassland, 24 percent; woodland, 27 percent; and urban, water and miscellaneous land uses the remaining 3 percent. We partitioned Court Creek into 300-by-300 foot parcels (2.07 acres per parcel), creating a total of 29,815 parcels or individual decision units. This parcel size was chosen because it leads to parcels that are relatively homogenous in their soil characteristics and slope while also ensuring that the number of land parcels does not exceed the upper limit for total number of cells imposed by the Agricultural Non-Point Source Pollution (AGNPS) model, the hydrologic model we use to predict non-point source pollutant loadings in agricultural watersheds. Furthermore, the first three of these 300 square feet parcel generally capture most of the floodplains of the tributaries of the Illinois River and therefore are eligible for enrollment in CREP.

A mix of GIS data, publications, and expert advice were used to parameterize AGNPS to reflect hydrological conditions in the watershed. A satellite image of the watershed was used to assign landuse to the parcels (Illinois Department of Natural Resources, 1996). This initial distribution of landuse also became our base for judging performance among the various policy alternatives. Digital Elevation Model (DEM) data from the US Geological Survey (1996) were collected and subroutines were written that assigned slope and slope length to every parcel. We wrote another subroutine that used each parcel's slope and aspect to create 2,318 flow paths or channels ranging in length between one parcel and 3 parcels to capture the flow of runoff water in the CREP eligible region of the watershed. Of these flow paths, 277 consisted of only 1 parcel, 563 consisted of two parcels and 1,478 consisted of 3 land parcels[3].

Other AGNPS parameters including Curve Number (CN), Manning's coefficient (N), surface condition coefficient (SC), cropping factor (C), conservation factor (P), and chemical oxygen demand (COD) were obtained from USDA publications (USDA, 1972, 1986) and adjusted by state Natural Resource Conservation Service (NRCS) professionals to take into account local conditions. Knox County's Soil Survey (1995) provided the necessary soil characteristics such as soil texture and erodibility. We obtained rainfall data from the Illinois State Water Survey (Huff and Angle, 1989).

Farm financial and production data were developed for a 700-acre grain farm, the averaged-sized commercial operation in Northwestern Illinois (White 1995, Siemens 1998). Acreage was split equally between corn and soybean production with corn and soybeans being planted using reduced-till[4] and no-till[5] systems, respectively. We used production guidelines in the Illinois Agronomy Handbook (1999) to identify initial seed, fertilizer and other input levels. The publication "Soil Productivity in Illinois" (1978) combined with expert advice from a soils expert (Olson, 1999) helped us to determine crop yields by soil type and slope and to fine-tune fertilizer use with expected yields. For corn, estimated crop yields varied between 82 and 188 bushels per acre; for soybeans, between 26 and 60 bushels per acre. A

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[3]. For paths with less than 3 parcels, the number of enrollment options are 4 (=2^2) and 2 for single parcel paths.

[4]. Reduced-till has less intensive operations on soil than conventional tillage such as smaller cultivation equipment.

machinery program developed by Siemens (1998) was used to identify suitable machinery sets and their associated costs. We collected 1998 output and input prices from various state sources. Using this data, we constructed crop budgets and calculated quasi-rents, defined as total revenues minus total variable costs, for all combinations of soils and slopes. Estimated per acre revenues, variable costs, and quasi rents for our representative 700-acre corn and soybean farm ranged between $221 and $345, $160 and $191, and $61 and $154, respectively. Again, subroutines were written that aggregated production and financial information and assigned it to each of the parcels.

Of the 29,815 parcels in the watershed, only 5,837 parcels (12,083 acres) fall within 900 feet of a stream on either side. In some cases, one or more of these parcels were currently non-cropland such as woodland or grassland, in which case their land-use was kept as such and they were not considered eligible for enrollment. This left us with 3,948 parcels with 8,172 acres of cropland that were eligible to enroll in CREP.

Summary statistics for the eligible CREP land parcels are provided in Table 1. As shown there the land parcels differed considerably in their slopes, quasi-rents per acre, their on-site erosion and nitrate generation and their slopes. While 41% of watershed is gently sloped with slope under 2%, there is still considerable variability in slope with a range 0.5% to 15%. The amount of sediment reaching each 3-parcel channel also varied across the channels between 0 and 63 tons. While some parcels had very erodible soil and generated 55 tons of on-site erosion others were less erodible and generated only 1.1 tons of on-site erosion.

V. Results

The 3,948 land parcels that were considered eligible for enrollment in CREP covered an area of 8,172 acres and earned a total quasi-rent of $ 909,926 per year with soybeans on half the acreage beans and corn on the other half using reduced tillage. With a 5-year storm event leading to 3.73 inches of rainfall for 12 hours, a run-off of 18,640 tons of sediment and 15,083 pounds of nitrates would be loaded

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[5]. No-till does not allow operations that disturb the soil other than the planting or drilling operation.

into water-body in the watershed given its existing pattern of land-use. The optimization model was run with both sediment and nitrate constraints restricting each type of pollutant to 10%, 15%, 20%, 25% and 30% of base levels for three different storm events (5 year, 25 year and 50 year events). In each case, we found that the corresponding nitrate constraint was not binding, in that achievement of the sediment abatement goal led to over achievement of the nitrate abatement goal. To achieve the 20% sediment abatement goal under 5-year storm events, the optimal model determines that 11% of the eligible acreage and land parcels should be targeted for enrollment in CREP (Table 2).

A comparison of the land parcels that should optimally be selected for enrollment under 5-year storm events with those that are eligible but not selected shows that 68% of the selected land parcels are adjacent to the river (Table 3). Only 5.3% of the selected parcels are the third parcel (furthest away from the river) in the 3-parcel channel. The selected land parcels also have low productivity index and low quasi-rents on average as compared to the land parcels that are not selected for enrollment. Additionally, the selected parcels have much higher slope and on-site erosion and nitrate run-off levels with crop production and belong to channels that are receiving a relatively larger volume of sediment inflows and nitrate inflows from upland areas. This indicates that although the off-site sediment contamination by a land parcel depends considerably on its on-site erosion levels and nitrate generation levels, it also depends on the location of the land parcel. The parcels selected are those right next to the river, that is those that did not have the benefit of having downstream parcels on which to deposit their sediment. Hence, selection of land parcels with high on-site erosion that are next to the river is optimal since it would have a substantial impact on reducing sediment loading in the river. Among the parcels with high contribution to the sediment loading, optimal targeting requires choosing those parcels with the lowest forgone benefits. As a result, the average quasi-rent of the selected cells is smaller than of the non-selected cells.

Alternative Land Rental Payment Schemes

To induce the selected land parcels to voluntarily retire land from crop production, policy makers could design a land-rental payment scheme that is based on a uniform payment per ton of abatement achieved by retiring the land parcel. Such a policy would be a cost-effective strategy for achieving the given sediment and nitrate abatement goals. For achieving the 20% sediment and nitrate abatement goals, a land rental payment policy that offers \$33.6/ton of abatement through land retirement would be cost-effective. If information were available on the amount of abatement that retirement of a land parcel would achieve then the per acre payment that would accrue to that land parcel if retired could be determined (=\$33.6 * abatement per acre). If this payment is greater than the quasi-rent per acre from crop production then it is optimal to retire the land from crop production. Given the heterogeneity in the quasi-rents and abatement potential of different land parcels in the watershed, rental payments based on this policy are likely to be greater than the quasi-rents per acre for all the inframarginal parcels selected by the optimal solution. For the marginal parcel that is selected, the land rental payment offered would be just equal to the quasi-rent per acre. Therefore the inframarginal land parcels will earn a surplus over and above their forgone quasi-rents. The total payment required for achieving the 20% sediment abatement goal is \$125,260 annually. If instead of paying a uniform price per ton of abatement, the policy maker could practice perfect price discrimination in its rental payment per ton of abatement offer across the selected land parcels then the minimum payment need to retire land would be exactly equal to the forgone quasi-rents from crop production. The costs of abatement incurred under such a policy would be \$70,310 annually. The difference \$55,000 represents the surplus transferred to the landowners under a uniform \$/ton abatement rental payment scheme.

The implementation of the optimally targeted enrollment in CREP using uniform payments per ton of abatement requires information on the abatement that would be achieved by each land parcel retired from crop production. To implement the perfectly price discriminating rental payment scheme policy makers also need information on the quasi-rents per acre earned by each of the selected land parcels. The abatement per acre achieved by enrolling a land parcel depends not only on the site-specific characteristics of the land parcel, such as its slope, distance from river and soil type, but also on the land use decisions made by parcels upstream and downstream from it in the run-off channel which are themselves endogenous to the land rental payment scheme that is offered.

To quantify the impact of various site-specific characteristics on abatement by the optimally targeted parcels and determine rental payments to the selected parcels, we disaagregated the total abatement achieved by each 3-parcel channel into the contribution of each parcel in that channel retired from crop production. We then examined the factors that influenced the magnitude of these ex post rental payments to the selected land parcels by regressing them on observable site-specific characteristics. The results of this regression are presented in Table 4. In Model I only the selected land parcels, that is those with non-zero land rental payments, are included. In Model II all eligible land parcels are included, that is, even those that receive a zero land rental offer under the optimal solution. The results obtained using both Models I and II show that abatement and therefore rental payment offers should increase as the distance of the parcel from the river decreases, as the slope of the parcel increases and as its erodibility index increases. Land parcels in channels that receive a larger volume of sediment inflow from upland areas should also be offered larger rental payments to induce enrollment. The results of Model I and II differ in the direction of impact of the productivity index of the land parcels on rental payment offers made to them. Model I shows that among the selected land parcels, the rental payment offered increases as the productivity index and therefore the forgone quasi-rent per acre of that parcel increases. Model II shows that among all eligible land parcels, land rental payments decrease as the productivity increases, because it is optimal to provide greater incentives for the less productive land parcels to enroll first.

Uniform Land Rental Payment per Acre

The implementation of a land rental payment scheme that depends on the abatement achieved by each land parcels is difficult to implement due to its informational requirements and due to the endogeneity of the abatement level to the land-use decisions made by other land parcels in the run-off channel. Policy makers may therefore choose a simpler land rental payment scheme based on uniform payments per acre of land retired. Such a policy would encourage land parcels with quasi-rents per acre that are lower than the uniform payment per acre to enroll. The pattern of enrollment generated by this policy is unlikely to replicate the optimal land retirement decisions because the land parcels with the lowest quasi-rents per acre may not be those that have the largest abatement potential. We find that a payment of $83.5 per acre is needed to induce land retirement such that the sediment abatement constraint of 20% can be achieved. This land rental payment reduces nitrate generation by 21%. The acreage that needs to be enrolled to achieve the 20% abatement goal is 28% larger than under the uniform $/ton of abatement land rental scheme. Although total government payments (Rent $/Acre times number of acres) is smaller than with the optimal targeting, the costs of abatement (forgone quasi-rents due to land retirement) are 38% higher than with the other land rental policy.

The uniform rental payment per acre enrolled policy does not create incentives to retire land parcels based on their contribution to abatement of sediment loadings and as a result the percentage of retired land parcels adjacent to the river is smaller than in the case of the optimal land rental payment scheme. Of the land parcels retired to achieve the 20% sediment abatement, 19.5% are parcels furthest from the river while 37% are the middle land parcels and only 44% are those closest to the river. As shown in Table 3, the targeted parcels under the $/acre enrolled policy are on average further from the river, had flatter slopes, smaller on-site erosion and nitrate run-off and belonged to channels that on average are receiving smaller sediment and nitrate run-off from upland areas in the watershed. As a result, the abatement efficiency of this pattern of land retirement per acre of land retired and per dollar of forgone quasi-rents is much smaller than under the optimal policy.

Sensitivity Analysis

We examine the sensitivity of the pattern of land retirement and costs of abatement to the desired abatement target for sediment and nitrate loadings in the river and to the intensity of the rainfall event. As shown in Table 2, as the abatement target becomes more stringent, costs of abatement increase steeply under both the optimal land rental policy and the uniform $/acre rental policy. The cost of abatement curve is upward sloping and convex as expected from our theoretical model and these costs are not very sensitive to the rainfall event considered. Figure 1 shows that costs of abatement for given percentage levels of sediment abatement increase as the intensity of the storm event increases. However, the difference in these costs across storm events is not very significant. At all levels of abatement, costs of abatement are higher under the \$/acre rental payment policy than under the \$/ton abatement rental payment policy as shown in Fig. 2 and Table 2.

VI. Conclusions

Soil conservation programs are increasingly targeting land retirement to achieve off-site sediment abatement and improvements in water quality rather than reduction in on-site erosion. The relationship between on-site erosion and off-site damages is dependent not only on the volume of on-site erosion but on the site-specific characteristics of the intervening land parcels in the path of the sediment flow and the landuse decisions made by those intervening land parcels. Land parcels that are closer to the water-body trap sediment flowing from upland parcels and provide an externality benefit to those upland parcels by reducing the off-site damages due to sediment generated on those upland parcels and should be compensated for it.

This paper develops a framework to determine the optimal pattern of land retirement in a watershed to achieve sediment and nitrate run-off abatement at least cost. By integrating detailed GIS data with a hydrologic model, this framework incorporates the inter-dependence between the sediment deposition ratios of land parcels in a run-off channel. It develops an economic model that incorporates this endogenous relationship between on-site erosion and off-site sediment loading from a land parcel for identifying the land parcels that should be targeted by a social planner for enrollment in a cost-effective soil conservation program.

The empirical results show that retirement of only 11 percent of the eligible cropland is sufficient to meet the program's 20 percent sediment abatement goal under a typical storm event in that region. This also reduces nitrate run-off by 22.5 percent, thus achieving CREP's second goal of nitrate reduction. We find that the optimal targeting of the program should be towards land parcels that have higher slope, are closer to the river and less productive in crop production. Additionally, downstream land parcels that are in the run-off path for a larger number of upland parcels, thus offer greater sediment trapping benefits relative to other land parcels, should be given higher priority when targeting CREP enrollment.

The implementation of the social planner's choice in a decentralized setting requires the provision of economic incentives to land owners to voluntarily retire their land. The paper analyzes the properties of the optimal rental payment mechanism required to achieve cost-effective abatement and shows that rental payment offers need to vary with the spatial location and characteristics of the land parcels. Such a policy would be difficult to implement due to its informational requirements. Instead, soil conservation programs have typically offered uniform $/acre rental payments to landowners. We find that the cost of achieving 20% sediment and nitrate abatement under a uniform rental payment policy that ignores differences in location and slope as well as the endogenous sediment deposition ratios is 38% higher than that with the optimally targeted enrollment. Finally, sensitivity results show that costs of abatement increase significantly as the environmental goals become more stringent and seek reductions in sediment above the 20% abatement level.

Table 1 Summary Statistics for Eligible CREP Land in the Court Creek Watershed

Variable	**Mean (Std. Dev)**	**Minimum**	**Maximum**
Quasi-rent ($/Parcel)	230.5 (68.1)	125.8	319.6
Distance from river (Feet)	585.3 (236.1)	0	900
Slope (%)	3.3 (3.5)	0.5	15
Erodibility Index	0.34 (4.44)	0.14	0.39
Sediment flow from upland to each 3-parcel channel (Tons)	2.68 (4.44)	0	62.9
Nitrate flow from upland to each 3-parcel channel (lbs)	13.94 (10.91)	0.25	51.67
On-Site Erosion (Tons)	8.8 (9.3)	1.1	55.4
On-Site Nitrate Run-off (lbs)	26.9 (14.5)	26.9	97.1
Productivity Index	127.5 (20.3)	65.3	153.8
No. of eligible land parcels	3,948		
No. of eligible land parcels in Position 1,2,3(1)	1,324, 1,494, 1,130		
Eligible Acres	8,172.4		

(1)Position 1 represents the one next to the river while Position 3 represents the one furthest from the river.

Table 2: Costs of Abatement for Alternative Abatement Levels with a 5-year Storm Event[1]: Comparison of results with optimal targeting and uniform land rental offers

Sediment Abatement Goal		10.0%	15.0%	20.0%	25.0%	30.0%
Optimal Targeting of CREP						
Nitrate Abatement Achieved		12.0%	16.5%	22.5%	27.3%	32.7%
Acreage Enrolled (acres)		310.5	565.1	900.5	1347.6	1966.5
Number of Land Parcels		150	273	435	651	950
Number of Land parcels grouped	1	121	204	296	400	536
by position in the channel[2]	2	26	60	116	194	300
	3	3	9	23	57	114
Loss of Quasi-rent (‘ 000 $)		23.25	43.2	70.31	108. 64	166.31
Government Payment with uniform price per unit of abatement (‘000 $)		33.87	70.48	125.26	234.76	434.59
Average Cost of Abatement ($/Ton)		12.5	15.5	18.9	23.4	29.8
Marginal Cost of Abatement ($/Ton)		18.2	25.3	33.6	50.5	77.9
Rental Payment Per Acre ($/Acre)		109.1	125.6	139.1	174.2	221.0
Uniform $/Acre Land Rental Payment Policy						
Nitrate Abatement Achieved		10.9%	16.0%	21.1%	26.6%	31.7%
Acreage Enrolled (acres)		486.5	784.5	1,244.1	1,707.8	2,647.5
Number of Land Parcels		235	385	601	825	1,282
Number of Land parcels grouped	1	115	180	262	339	465
by position in the channel	2	77	139	222	310	501
	3	43	66	117	176	306
Loss of Quasi-rent (‘ 000 $)		35.59	58. 93	97.21	135.94	217.89
Government Payment with uniform price per acre (‘000 $)		36.16	65.54	103.93	142.67	233.25
Average Cost of Abatement ($/Ton)		19.1	21.1	26.1	29.2	39.0
Rental Payment Per Acre ($/acre)		74.3	83.5	83.5	83.5	88.1

[1] A 5 year storm event represents 12 hours of rainfall amounting to 3.73 inches. In the absence of any enrollment, the base level of sediment run-off is 18,604.0 tons and nitrate run-off is 15083.0 lbs.

[2] Parcel 1 represents the one next to the river while Parcel 3 is furthest from the river

Table 3. Comparison of the Characteristics of the Targeted vs. Non-Targeted Land Parcels Under Alternative Land Rental Schemes for 20% Sediment Abatement

	Targeted	**Non-Targeted**	**Targeted**	**Non-Targeted**
Variable	**Optimal Land Rental ($/Ton of Abatement)**		**Uniform Land Rental ($/Acre of Enrollment)**	
Quasi-rent ($/Parcel)	161.8	319.6	161.7	242.8
Distance from river (Feet)	411.7	606.8	527.6	595.6
Slope (%)	10.1	2.5	9.5	2.2
Erodibility Index	0.37	0.33	0.37	0.33
Sediment flow from upland to each 3-parcel channel (Tons)	5.19	2.37	4.10	2.42
Nitrate flow from upland to each 3-parcel channel (lbs)	14.0	4.4	12.5	4.2
On-Site Erosion (Tons)	28.3	6.4	25.2	5.89
On-Site Nitrate Run-off (lbs)	58.4	20.7	53.4	19.7
Productivity Index	108.6	129.9	108.7	130.9
Acres (%)	11	89	15.2	84.8
Land Parcels (%)	11	89	15.2	84.8
First Parcels Selected (%)	68.0	29.3	43.6	31.7
Second Parcels Selected (%)	26.7	39.2	36.9	38.0
Third Parcels Selected (%)	5.3	31.5	19.5	30.3

Table 4: Determinants of the Optimal Land Rental Payments for Enrollment

Dependent Variable: Optimal Rental Payment Per Parcel		
Independent Variables	Model 1	Model II
Intercept	-724.16 (594.96)	66.82 (52.57)
Distance from River	-0.253 (0.029)**	-0.064 (0.005)**
Slope of Parcel	22.15 (2.44)**	17.22 (0.39)**
Erodibility Index	1403.0 (1037.3)*	-72.03 (85.46)
Sediment from upland parcels	0.999 (0.638)*	1.21 (0.27)**
Productivity Index	3.40 (2.00)**	-0.27 (0.19)*
No. of Observations	435	3513
R^2	0.28	0.46

Note: ** indicates significance at 1%, * at 10%. Standard errors in parentheses

Figure 1: Total Costs of Abatement under Alternative Rainfall Events

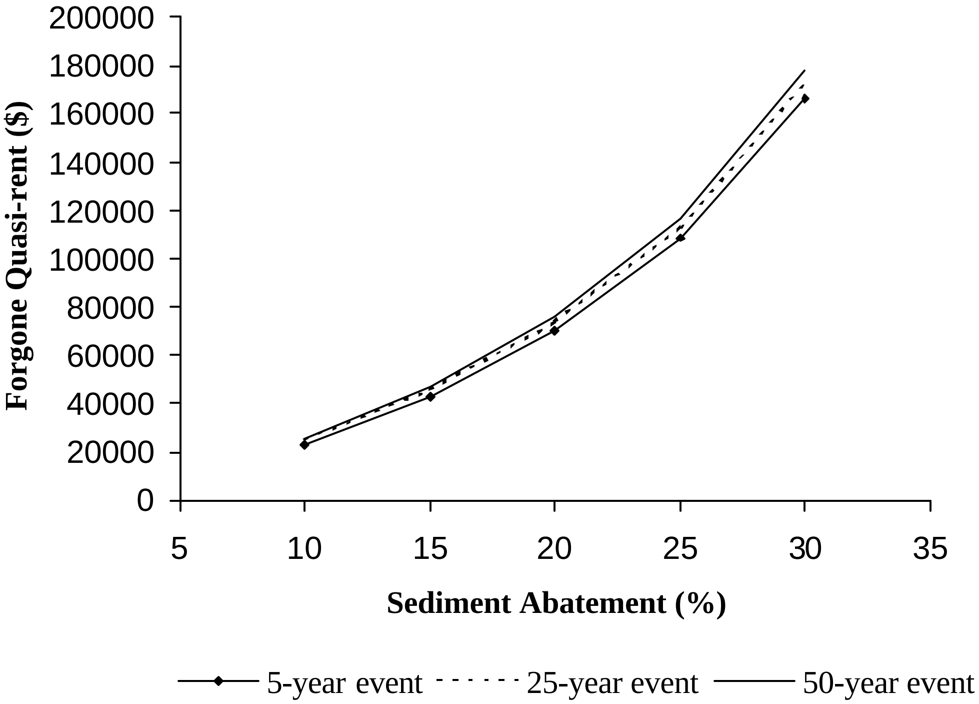
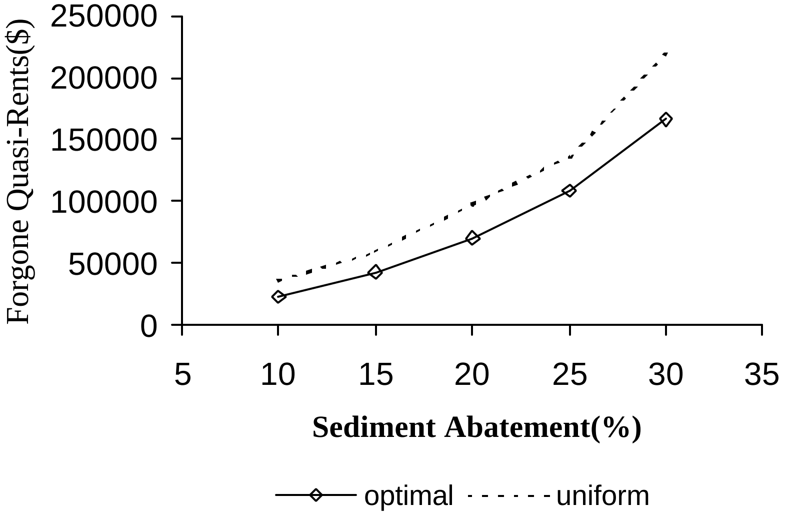


Figure 2: Total Abatement Costs under Alternative Land Rental Payment Schemes



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