Multiple Benefits of Carbon-Friendly Agricultural Practices: Empirical Assessment of Conservation Tillage

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Abstract

In this study, we estimate empirically the multiple benefits of a subsidy policy that would offer payments to farmers in return for the adoption of conservation tillage and compare the outcomes of alternative targeting designs for such a policy. Using data for roughly 12,000 National Resource Inventory (NRI) points, we simulate for the state of Iowa the least-cost policy schemes for offering payment incentives. We use an economic model of conservation tillage adoption to evaluate the costs of adoption, and we use a model that simulates physical processes (Environmental Policy Integrated Climate, or EPIC) to estimate the environmental benefits of adoption at each of the NRI points.

We assess the costs and environmental consequences of two targeting options. The first is a practice-based policy instrument that maximizes the acres of land in conservation tillage, regardless of the level of environmental benefits achieved. The second is a performance-based instrument that yields the highest amount of environmental benefits per dollar spent. We consider four performance-based benefits: carbon sequestration in agricultural soils, reduction in nitrogen runoff, reduction of erosion of soil by wind, and reduction of erosion of soil by water. We find that the practice-based instrument provides high proportions of the four benefits relative to the performance-based instrument, especially at higher budget levels. Similarly, we estimate that targeting one of the four benefits provides high percentages of the other benefits compared to the amounts obtainable if they were targeted directly.

Keywords: conservation tillage, multiple benefits, subsidy policy, targeting.

MULTIPLE BENEFITS OF CARBON-FRIENDLY AGRICULTURAL PRACTICES: EMPIRICAL ASSESSMENT OF CONSERVATION TILLAGE

The prospect of sequestering carbon in agricultural soils has generated substantial interest both in the scientific community and among policymakers. Lal et al. (1998) estimate the physical potential of U.S. cropland to sequester carbon at between 75 and 208 million metric tons of carbon per year. This physical potential cannot be realized, however, without policies that take into consideration farmers' profit motives. Policies under discussion include formal carbon markets and direct incentive payments (subsidies) to farmers through a government program.

A subsidy program might be offered under the auspices of the Conservation Security Program (CSP), a key conservation feature of the 2002 Farm Security and Rural Investment Act. Under the CSP, farmers are paid for the adoption of environmentally friendly practices such as conservation tillage. This subsidy policy could be designed to cost-effectively induce adoption of conservation tillage if, for example, a bid mechanism similar to that used for the Conservation Reserve Program (CRP) were employed. However, while such a policy might yield the least-cost adoption of the practice of conservation tillage, it is not necessarily efficient for the provision of environmental benefits, as farmers are paid for practices as opposed to the resulting environmental benefits. To the extent that different farms yield different environmental benefits because of differing soil and land characteristics, a more efficient policy would target areas that are more environmentally sensitive.

In this paper, we compare the least-cost policy design based on practice, which we simply refer to as the practice-based policy, to a more efficient alternative, which we call the performance-based policy. The performance-based policy would still pay for the adoption of the practice, but it would target it toward the environmental benefit by offering the subsidy first to the producers that can provide the highest amount of benefit per dollar spent (until the policy budget is exhausted).

In addition to carbon sequestration benefits, conservation tillage can generate a range of positive environmental externalities related to soils, water quality, and wildlife habitat. Recent research has provided estimates of these benefits under varying scenarios of adoption (e.g., Baylis et al. 2002). However, relatively little information exists on the costs of attaining these benefits or on which policies are best for achieving environmental goals. Our study aims to fill part of this gap by evaluating the multiple benefits from adoption of conservation tillage.

Given the multiple benefits of conservation tillage adoption, a performance-based policy can be based on different environmental indicators. For example, a policymaker might pay farmers for their contribution to reduced soil erosion. In this case, carbon sequestration, as well as the other environmental benefits, could be thought of as a co-benefit, and an important question is how efficient a soil-erosion-based performance policy is for carbon sequestration. That is, if a subsidy policy that targets reduction of soil erosion is implemented, how much less carbon is sequestered than if carbon sequestration were targeted directly? Or, alternatively, if a policy that targets carbon sequestration is implemented, how much less nitrogen runoff reduction is achieved than if nitrogen reductions were targeted?

The objective of this paper is to estimate empirically the multiple benefits of the practice-based policy as well as the performance-based policy that target such environmental benefits as carbon sequestration, reduction of soil erosion by wind and by water, and nitrogen runoff reduction. These policy schemes are simulated for the state of Iowa using data for some 12,000 National Resource Inventory (NRI) points (Nusser and Goebel 1997). We use an economic model of adoption of conservation tillage to evaluate the costs of adoption. To estimate the environmental benefits, we use a model that simulates physical processes to calculate the changes in nitrogen runoff, soil erosion, and soil carbon accumulation in response to the adoption of conservation tillage at each of the NRI points.

In practice, there will be a trade-off between the practice-based policy and the more efficient performance-based policy in terms of costs of implementation. Specifically, the practice-based policy should have relatively smaller costs of measuring and monitoring compliance whereas the performance-based policy is likely to have higher implementation costs. While the existence of this trade-off is well understood, evaluation of its magnitude is an empirical question that has received little attention in the literature on carbon sequestration in agricultural soils. Antle et al. (2003) evaluate the relative costs of practice-based versus benefit-based policies in the context of a policy that pays for a change in cropping systems in grain-producing regions of Montana. In the conservation tillage context, Pautsch et al. (2001) partially evaluated the trade-off by comparing a performance-based policy to a policy that offers the same per-acre subsidy to all adopters (and as such is not the least-cost practice-based policy).

In the next section, we present a theoretical model of alternatives for the design of subsidy policies, followed by a discussion of the empirical models and the data used in the analysis. We proceed with estimation of environmental benefits for a practice-based policy, followed by the study of relative efficiencies of alternative policy designs for targeting environmental benefits.

Methods

Alternative Policy Designs for Targeting Benefits

To model the subsidy policy, suppose there are N farms, indexed by $n = 1,...,N$, and there are K environmental amenities, indexed by $k = 1,...,K$. For simplicity, we assume that all farms are of equal size, normalized to one, and the land on a particular farm is homogenous. Given a subsidy of C_n, farm n adopts conservation tillage with probability $p_n(C_n)$, and the environmental improvements from the adoption are $X_n = (X_n^1,...,X_n^K)$. We assume that the policymaker knows the adoption probability function $p_n(\bullet)$ (through, for example, estimating farm n's bid in a program similar to CRP sign-ups) and focus on possible least-cost incentives for the design of payment policies.

First, consider the practice-based policy that targets conservation tillage without regard to its environmental benefits. That is, given a total budget C, the policymaker wishes to maximize the expected amount of land in conservation tillage by providing subsidy C_n to farm n:

$$A^{*}=\max_{C_n,n=1,\dots,N}\sum_{n=1}^{N}\left\{p_n\left(C_n\right)-p_n\left(0\right)\right\}\ \ s.t.\ \ \sum_{n=1}^{N}p_n\left(C_n\right)C_n=C\ ,\ \ 0\le C_n,\quad n=1,\dots,N\ . \quad (1)$$

Notice that the objective function measures the expected acreage enrolled because each farm is normalized to have one acre of land. Also, the total amount of land in conservation tillage expected without the subsidy is subtracted from the total amount of land in conservation tillage expected with the subsidy. This allows for a more precise evaluation of the policy effect on adoption. However, consistent with the provisions of the CSP (U.S. Congress 2002), we assume that payments will be provided to all producers, both current and new. The budget constraint requires that the expected total cost cannot exceed budget C .

Let λ be the Lagrangian multiplier associated with the cost constraint. The optimality conditions are

$$\begin{aligned}&p_n^{'}(C_n)-\lambda p_n^{'}(C_n)C_n-\lambda p_n(C_n)\le 0;\qquad C_n\ge 0;\\&[\,p_n^{'}(C_n)-\lambda p_n^{'}(C_n)C_n-\lambda p_n(C_n)]C_n=0.\end{aligned} \quad (2)$$

Depending on the adoption probability function, some farms may receive zero subsidies (i.e., $C_n=0$), and some farms may enroll with zero probabilities.

If the policymaker wishes to maximize the expected aggregate amount of the *k*th environmental amenity from the program, then the problem is

$$X^{k^{*}}=\max_{C_n,n=1,\dots,N}\sum_{n=1}^{N}\left\{p_n(C_n)-p_n(0)\right\}X_n^k\quad s.t.\quad \sum_{n=1}^{N}p_n\left(C_n\right)C_n=C\ ,0\le C_n,\,n=1,\dots,N\ . \quad (3)$$

Let λ^k be the associated Lagrangian multiplier, then the optimal solution is characterized by

$$\begin{aligned}&p_n^{'}(C_n)X_n^k-\lambda^k p_n^{'}(C_n)C_n-\lambda^k p_n(C_n)\le 0;\qquad C_n\ge 0;\\&[\,p_n^{'}(C_n)X_n^k-\lambda^k p_n^{'}(C_n)C_n-\lambda^k p_n(C_n)]C_n=0\end{aligned}\ . \quad (4)$$

Comparing (4) with (2), we see that, by weighting the adoption probability with benefit X_n^k, the optimal subsidy to farm n will be higher as X_n^k increases. Again, farms providing low levels of the *k*th amenity may receive no subsidy or may enroll with zero probability.

If the farms are heterogeneous in the environmental benefits from adoption of conservation tillage, then the optimal subsidy levels in the two programs will differ. Also, the optimal subsidy levels possibly may differ depending on which of the benefits is targeted. The environmental benefits from alternative targeting schemes will be less different as the farms become more homogeneous in X_n. In the extreme, if all farms are the same, i.e., if X_n is the same for all n, the subsidy levels under all programs will be the same, and the targeting schemes will be equivalent to each other. In this study, we simulate policy designs (1) and (3) for alternative subsidies under varying budgets C to assess the multiple environmental benefits generated by the policies.

Costs and Environmental Amenities of Conservation Tillage Adoption

In estimating the costs of adoption of conservation tillage C_n, we draw on the work of Kurkalova, Kling, and Zhao (2001), who present a methodology and empirical estimates of a reduced-form, discrete-choice adoption model for Iowa. Here, we briefly summarize this model and explain how we use it and then describe the physical process model, EPIC (Environmental Policy Integrated Climate), that we employ to simulate the environmental benefits associated with changes from conventional to conservation tillage (i.e., the X_n's). These two models are used jointly to estimate the costs and amenities of adoption on some 12,143 NRI points for the state of Iowa.

The Kurkalova, Kling, and Zhao (2001) model is derived under the assumption that a farmer will adopt conservation tillage if the expected annual net return from conservation tillage exceeds that expected from conventional tillage plus a premium associated with uncertainty, which, in turn, depends on the variability of the net returns to conservation tillage and conventional tillage and other explanatory variables. In the model, the probability of adoption is expressed as a function of the production site's physical and climatic characteristics, the crop grown, and farmer characteristics, as well as the expected net return to conventional tillage. In particular, the adoption probability is $p_n(C_n) \equiv p(C_n, \overline{s}_n)$, where vector $\overline{s}_n$ is a collection of producer-specific variables, and $p(\bullet)$ is logistic. This adoption model is estimated on a random subsample of NRI points located in Iowa.

The basic data come from the 1992 NRI (USDA/NRCS 1994). The NRI data are statistically reliable for national, state, and multi-county analysis of nonfederal land (Nusser and Goebel 1997) and thus are reasonably representative of Iowa agricultural land. In our calculations, we treat each NRI point as representing a producer with a farm size equal to the number of acres represented by the point (the NRI expansion factor). The NRI provides information on the natural resource characteristics of the land and the crop grown (1992 and 1991 seasons). For additional information on the data source and model, see Kurkalova, Kling, and Zhao (2001).

The field-specific environmental benefits from conservation tillage X_n^K, $k = 1,...,K$, $n = 1,...,N$, are estimated at each of the data points using the EPIC model version 1015 (Izaurralde et al. 2002)[1]. EPIC is a commonly used simulation model adaptable for large regional analyses (e.g., Plantinga and Wu 2003; Babcock et al. 1997). The simulations are carried out at a field-scale level for areas homogeneous in weather, soil, landscape, crop rotation, and management system parameters. EPIC operates on a continuous basis using a daily time step and is capable of simulating multiyear periods. The model accounts for the effects of tillage on surface residue, soil bulk density, and mixing of residue and nutrients in the soil plow layer. Version 1015 of EPIC includes an updated carbon simulation routine that is based on the approach used in the Century model developed by Parton et al. (1994).

At each of the data points, two 30-year simulations are run, one assuming conventional tillage and the other assuming conservation tillage. The NRI database provides baseline land use and other input data for the simulations. The quantities of the four environmental benefits—sequestered carbon, reduction in nitrogen runoff, reduction in wind erosion, and reduction in water erosion—are computed as the differences between appropriate EPIC outputs under conservation tillage and those under conventional tillage, averaged over the 30 years.

Results

We simulated the policies at 40 budget levels roughly corresponding to the amount of federal funding potentially available to Iowa through the CSP.[2] Table 1 provides the environmental benefits creditable to the practice-based policy that targets conservation

TABLE 1. Multiple benefits of practice-based subsidy policy

Budget (Mil $)	Carbon Sequestered (1,000 Tons)	Nitrogen Runoff Reduction (Tons)	Water Erosion Reduction (Tons)	Wind Erosion Reduction (Tons)
2	41.309	59.494	156.13	163.11
6	109.94	155.61	393.65	460.82
10	169.46	236.74	597.49	704.02
14	223.09	308.38	781.66	917.34
18	272.47	374.55	951.39	1113.60
22	318.33	436.03	1111.50	1294.30
26	361.52	493.37	1260.80	1462.30
30	402.13	547.35	1403.30	1618.30
34	440.77	599.29	1538.00	1768.00
38	477.60	647.88	1666.20	1908.30
42	512.68	694.32	1788.80	2041.50
46	546.28	738.55	1907.30	2168.30
50	578.65	781.40	2020.20	2290.30
54	609.85	822.64	2129.30	2407.10
58	639.80	862.01	2234.30	2518.20
62	668.75	900.41	2336.10	2625.30
66	696.59	937.11	2433.60	2728.20
70	723.55	972.60	2528.20	2828.30
74	749.49	1006.80	2619.60	2923.10
78	774.67	1040.00	2708.20	3015.30

tillage. We found that such a policy can achieve carbon sequestration of around 0.169 million tons of carbon at a total cost of $10 million, with the co-benefits of reduced nitrogen runoff of about 236.74 tons, reduced erosion of soil by water of about 597.49 tons, and reduced soil erosion by wind of about 704.02 tons per year. As can be easily seen from Figure 1, the practice-based policy provides high proportions of the benefits obtainable from the policies that target the respective benefits.

Figure 2 contrasts the environmental amenities from the practice-based targeting and carbon-sequestration-based targeting at two budget levels: $2 million and two times that

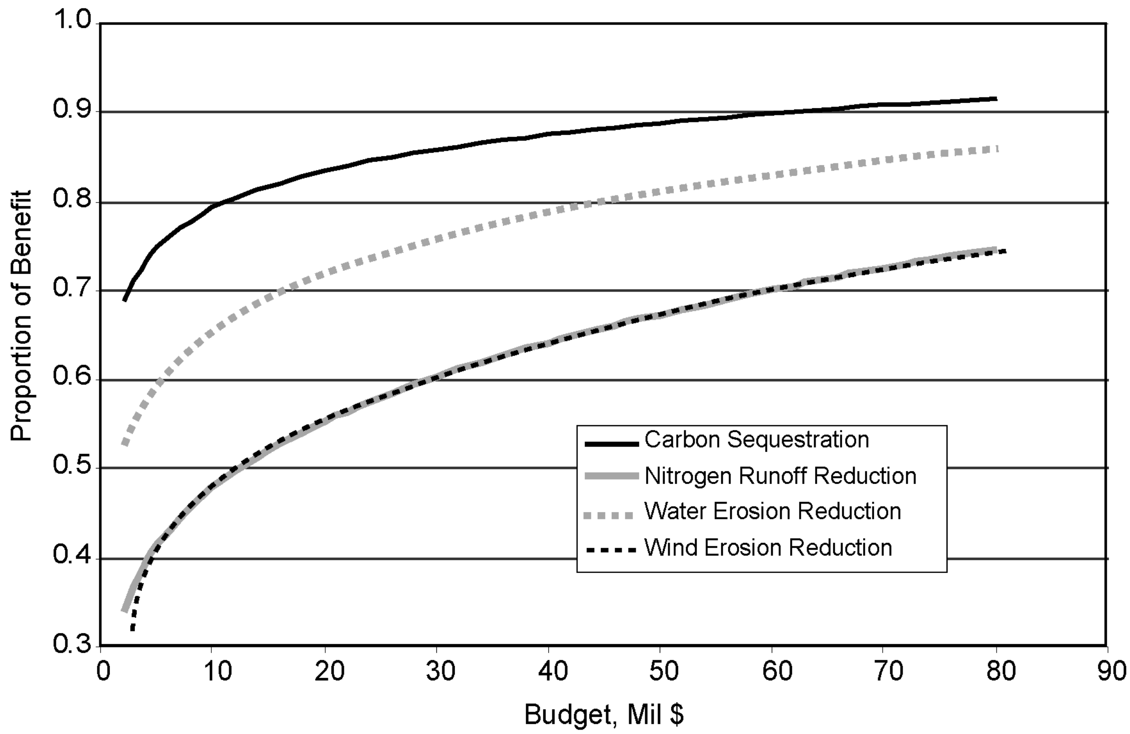

FIGURE 1. Benefits obtainable under practice-based policy as compared with results of direct targeting of benefits

level—$4 million. As expected, targeting carbon leads directly to more total carbon and less land area in conservation tillage as compared to targeting conservation tillage. The amounts of other benefits change with the alternative policy designs. For instance, we found that targeting carbon increases the reduction in nitrogen runoff and the reduction in wind erosion and decreases the reduction in water erosion as compared to a practice-based targeting.

Additionally, the figure shows that the environmental benefits have a concave relation to the budget level: a doubling of the budget leads to less than a doubling of the physical quantities of the benefits. This is because the farmers that provide environmental amenities at the lowest costs are selected into the program first, with the more expensive benefits being provided as the budget increases. Thus, the amount of benefits grows as policy funding increases, but at a decreasing rate.

To aid comparison of alternative targeting schemes, Figures 3 and 4 demonstrate how much less of a specific environmental benefit is obtained under a scheme that targets

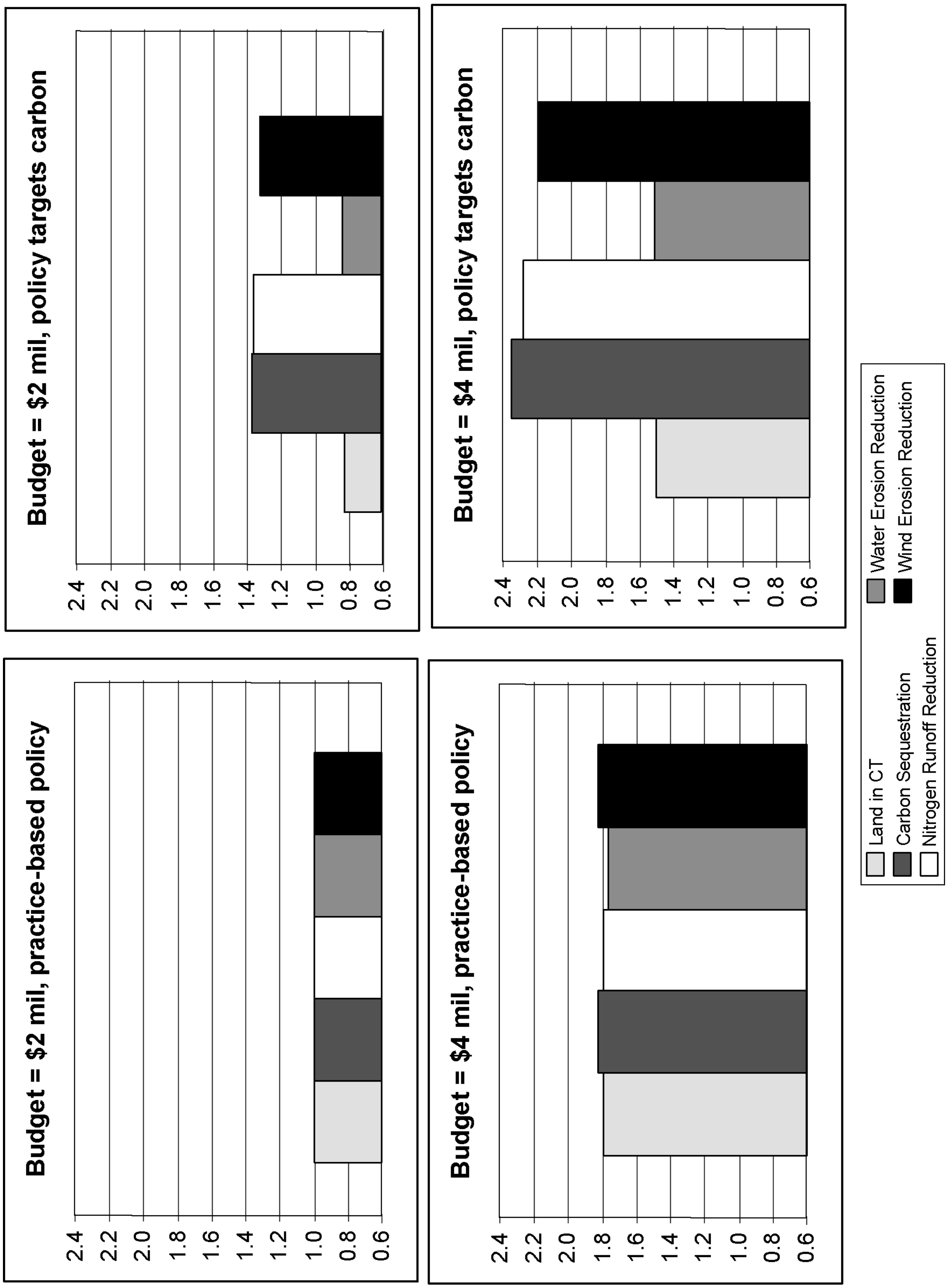

FIGURE 2. Benefits of practice- and carbon-performance-based policies at two budget levels

one of the other attributes, compared to the amount obtainable if this benefit were targeted directly. Figure 3 focuses on carbon, depicting the estimated proportion of carbon obtainable under alternative targeting schemes as compared to the amount of carbon obtainable when carbon is targeted, for varying budget levels. As expected, the proportions increase with the budget, as more and more farmers adopt conservation tillage and there is less room left for selectively choosing farmers into the program. At the extreme, when the budget level is adequate to enroll every farmer into the incentive payment program, targeting is no longer relevant for benefits obtained. But even at the lower, more realistic levels of the budget, more than 60 percent of the potentially obtainable carbon sequestration can be achieved in Iowa with the policies that target conservation tillage acreage or the other benefits in question. These results show that the farms are relatively homogenous in terms of the environmental benefits they can produce from their adoption of conservation tillage.

Figure 4 represents similar information but in terms of the proportions of co-benefits obtainable under carbon targeting. We found that alternative targeting schemes still result in high proportions of the maximum benefits obtainable for all the three co-benefits of carbon sequestration considered: reductions in nitrogen runoff, in water-induced soil erosion, and in wind-induced soil erosion. However, as can be seen from Figures 3 and 4, the policy that targets conservation tillage seems to be the most “correlated” with the policy that targets carbon sequestration in the sense that targeting either one provides high proportions of the other attribute.

Conclusions

This paper compares the relative efficiency of alternative targeting schemes for least-cost incentive policies that offer farmers subsides in return for adoption of conservation tillage. For the state of Iowa, the study provides estimates of the costs and benefits of policies that target conservation tillage acreage, carbon sequestration in agricultural soils, reduction in nitrogen runoff, reduction in water-induced soil erosion, and reduction of wind-induced soil erosion. We found that the least-cost policy that targets conservation tillage acreage provides high proportions of the four benefits relative to the policies that target the benefits directly, especially at higher budgetary levels of the policy. Similarly,

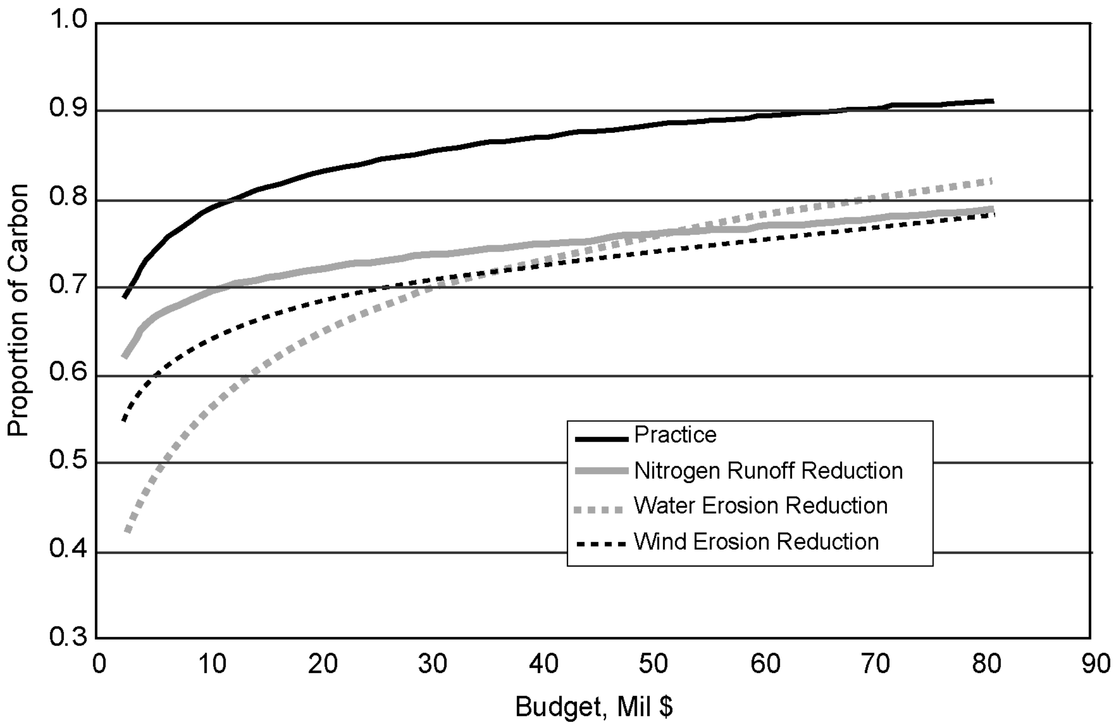

FIGURE 3. Carbon sequestered under alternatively targeted policies as compared with results of direct carbon targeting

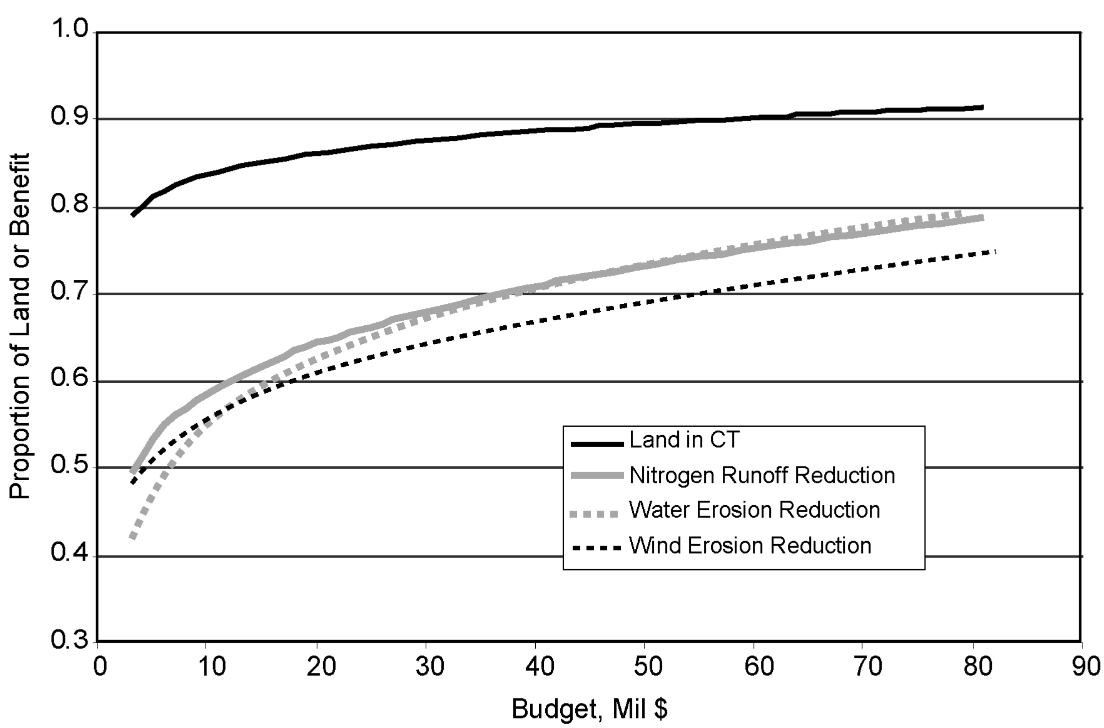

Figure 4. Land in conservation tillage and benefits under the carbon-targeting policy as compared with direct land or benefits targeting

we estimated that targeting one of the four benefits provides high percentages of the other benefits as compared with the amounts of the benefits obtainable if they were targeted directly.

This finding implies that, especially when budgets are ample, there may be no need for implementation of performance-based subsidy policies for which monitoring costs are likely to be high. In this case, the variability of soil and weather characteristics in the region may be not high enough to justify the transaction costs to be incurred in the design and implementation of the subsidy policies that target any of the environmental benefits considered.

It must be noted, however, that our results are not immediately transferable to areas outside of Iowa, as the findings reflect the unique variability of natural resources in the study region. Nor are the results applicable to agricultural practices other than conservation tillage, as correlations among the benefits may be different for other carbon-friendly agricultural practices.

We also note that the estimates of the costs and benefits of the policy designs depend on the estimates derived from the EPIC model. While the model is continuously improved and calibrated against controlled experimental data (e.g., Izaurralde et al. 2002), physical process modeling errors are inevitable. A useful extension of our study would involve an analysis of sensitivity to EPIC simulation outcomes through, for example, Monte Carlo simulation methods.

Finally, our results are obtained under an implicit assumption that the policymaker values at the same rate environmental benefits derived from different fields. As Antle and Mooney (2002) observe, this is likely to be a valid assumption when it pertains to the benefits of carbon sequestration for the reduction of greenhouse gases. Rephrasing Antle and Mooney, a ton of carbon sequestered in eastern Iowa is as good for battling the greenhouse effect as a ton of carbon sequestered in western Iowa. However, the benefits may be nonadditive when they are relevant to water quality: a reduction of nitrogen runoff close to a river may be more valuable to society than a reduction in nitrogen runoff from a field located miles from the nearest body of water. A follow-up study currently in the works accounts for the spatial nonadditivity of water-quality-related benefits by employing a physical simulation model that takes into account the spatial movement of nutrients and sediment in drainage areas.

Endnotes

1. Earlier versions of EPIC were called the Erosion Productivity Impact Calculator (Williams 1990).

2. The CSP of the 2002 farm legislation provides $2 billion for five years (U.S. Congress 2002). Even if Iowa crop producers get as much as one-fifth of the yearly total, the program funding is limited to $80 million per year.

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