Carbon Sequestration in Agricultural Soils: Discounting for Uncertainty

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Abstract

The study presents a conceptual model of an aggregator who selectively pays farmers for altering farming practices in exchange for carbon offsets that the change in practices generates. Under the assumption that the offsets are stochastic and that the aggregator maximizes the sum of the offsets from the purchase that he/she can rightfully claim with a specified level of confidence subject to a budget constraint, we investigate the optimal discounting of expected carbon offsets. We use the model to estimate empirically the optimal discounting levels and costs for a hypothetical carbon purchasing project in the Upper Iowa River Basin.

Keywords: carbon sequestration in agricultural soils, offset discounting, uncertainty.

CARBON SEQUESTRATION IN AGRICULTURAL SOILS: DISCOUNTING FOR UNCERTAINTY

Introduction

Agricultural communities in the United States, Canada, and in a number of other countries have been excited about the prospect of farmers selling credits for carbon sequestered in cropland soils as greenhouse gas emission offsets. However, one of the big practical issues hindering the potential carbon sales is the uncertainty associated with the offsets. From a buyer's point of view, future offsets are uncertain because carbon sequestration in agricultural soil is affected by a multitude of factors, many of which, such as weather and solar radiation, are inherently stochastic.

While there is a growing soil science literature quantifying the uncertainty and its determinants, the topic has received little attention in the economic analyses of carbon sequestration in cropland (Antle and McCarl 2002). Marland, McCarl, and Schneider (2001) mention the importance of the uncertainty in the context of proposed carbon accounting protocols that allow the credits only if there is at least 95 percent certainty about their magnitude. McCarl, Butt, and Kim (2004) also discuss the importance of the uncertainty and report the ensuing discounting of carbon offsets at the Chicago Climate Exchange at about 15 percent. Antle et al. (2003) propose a sampling procedure to reduce the uncertainty about carbon sequestered, yet neither study investigates how the presence of uncertainty alters economic agents' decision making. This study attempts to fill in this gap by analyzing the mechanism of discounting carbon offsets for uncertainty.

The focus of the current study is an aggregator, the economic agent vital for carbon trading involving agriculture, as large emitters of greenhouse gases usually need quantities of offsets much larger than any single farm can provide (Thomassin 2003; McCarl, Butt, and Kim 2004). In a carbon sequestration program administered by a government agency, the role of the aggregator is also important. In this case, the aggregator would assemble the offsets for reporting to interested parties such as those representing taxpayers (for domestic programs) or to certify international organizations (for international

agreements). In any case, because of either market requirements or policy design stipulations, the aggregator may be seriously concerned about the uncertainty of the offsets being delivered and may adjust behavior accordingly.

This study presents a conceptual model of an aggregator selectively purchasing carbon offsets from farmers who switch farming practices to those that increase soil carbon content. We assume that the aggregator maximizes the sum of the offsets from the project that he/she can rightfully claim with a specified level of confidence, subject to a budget constraint. The model builds on the earlier work on cost-efficiency of achieving probabilistic pollution reduction targets (see, e.g., Shortle and Horan 2001). Empirical applications of the approach have been limited and almost exclusively focused on water quality (Milon 1987; Lichtenberg, Zilberman, and Bogen 1989; Bystrom 1998; Shortle et al. 1999; Bystrom, Andersson, and Gren 2000). In contrast, we build the model specifically to examine expected offset discounting arising because of uncertainty in the amount of carbon to be sequestered and the aggregator's concern about confidence bounds on the total offset. We then apply the model to an empirical study of a hypothetical carbon sequestration project in the Upper Iowa River Basin.

Conceptual Model

Assume there are N farms indexed by i that can potentially change their current farming practice to that of sequestering carbon. Let $\bar{x}_i$ denote the size of farm in acres and let c_i be the per acre opportunity cost of farmer changing practice (known to the aggregator). The farm i per acre offset generated by the change in practice, b_i, is stochastic, and because of varying natural conditions (soils and landscape characteristics, cropping history, etc.), the offset distributions differ potentially from farm to farm, so that the b_i's are jointly normally distributed,

$$
\begin{pmatrix} b_1 \\ b_2 \\ ... \\ b_N \end{pmatrix} \sim N \left(\begin{pmatrix} \bar{b}_1 \\ \bar{b}_2 \\ ... \\ \bar{b}_N \end{pmatrix}, \begin{pmatrix} \sigma_{11} & \sigma_{12} & ...\sigma_{1N} \\ \sigma_{12} & \sigma_{22} & ...\sigma_{2N} \\ ... \\ \sigma_{1N} & \sigma_{2N} & ...\sigma_{NN} \end{pmatrix} \right),
\tag{1}
$$

where $\bar{b}_i \equiv E(b_i)$, $\sigma_{ii} \equiv Var(b_i)$, $\sigma_{ij} \equiv Covar(b_i, b_j)$, $i, j = 1,..., N$.

The aggregator is an economic agent who selectively offers farmers payments for switching the practices in exchange for carbon offsets that the change in practices generates. The aggregator has a budget, C, for these purchases, and for each farmer, i, the aggregator decides on the number of acres, x_i, $0 \le x_i \le \overline{x}_i$, on which to offer per acre payment c_i. We assume that as long as a farmer is offered the payment, he/she switches the practices and the aggregator acquires the offset.

Because of carbon market regulations (or those of the policy if the offset purchasing is done under auspices of a government-administered policy) the aggregator is concerned about the certainty of the total offset he/she is getting from the individual purchases. Specifically, we assume that the aggregator maximizes the amount of the aggregate offset that can be rightfully claimed with a confidence level α. The confidence level, α, is typically large and is greater than 0.5. Thus, the aggregator is maximizing the offset amount B, defined by

$$\Pr\left\{\sum_{i=1}^{N} b_i x_i \ge B\right\} = \alpha. \tag{2}$$

Under the assumptions (1), the total carbon sequestered in the program, $\sum_{i=1}^{N} b_i x_i$, is normally distributed with the expected value $\sum_{i=1}^{N} \overline{b}_i x_i$, and variance $\sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j \sigma_{ij}$. Therefore, the deterministic equivalent of (2) is

$$B = \sum_{i=1}^{N} \overline{b}_i x_i - z_\alpha \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N} \sigma_{ij} x_i x_j},$$

where z_α is the number such that $\Pr\{Z \le z_\alpha\} = \alpha$ and $Z \sim N(0,1)$ (Charnes and Cooper 1963). Note that if the aggregator is indifferent between falling below and exceeding the total offset target B, then $\alpha = 0.5$ and $z_\alpha = 0$, meaning that aggregator is not making any adjustments to the uncertainty of the total offset and is simply maximizing the total expected value of the offsets purchased. However $z_\alpha > 0$ as long as $\alpha > 0.5$, implying

that in this case the aggregator is always *discounting* the expected value of the total offset purchased by the amount

$$A \equiv z_\alpha \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \sigma_{ij} x_i x_j} \ . \tag{3}$$

As expected intuitively, the magnitude of discounting increases with the confidence level α and depends on the variability of offsets as described by their variance-covariance matrix.

Mathematically, the aggregator's problem is

$$\max_{x_1,\dots,x_N} \sum_{i=1}^{N} \overline{b}_i x_i - z_\alpha \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} x_i x_j \sigma_{ij}} \tag{4}$$

subject to the budget constraint $C - \sum_{i=1}^{N} c_i x_i \geq 0$, the N land constraints $\overline{x}_i - x_i \geq 0$, $i = 1,\dots,N$, and the N non-negativity constraints $x_i \geq 0, \quad i = 1,\dots,N$.

Let $x_i^*, i = 1,\dots,N$ denote the solution to (4), λ^* be the Lagrangian multiplier of the budget constraint at the optimum, and $\theta_i^*, i = 1,\dots,N$ be the Lagrangian multipliers of the land constraints at the optimum. Then the first-order necessary conditions imply that all positive x_i^* satisfy the equation

$$\overline{b}_i - z_\alpha \sum_{j=1}^{N} \sigma_{ij} x_j^* \bigg/ \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \sigma_{ij} x_i^* x_j^*} - \lambda^* c_i - \theta_i^* = 0 \ . \tag{5}$$

Intuitively that means that at the optimum, the farm i marginal per acre expected benefit $\overline{b}_i$ is being effectively adjusted by the amount $a_i^* \equiv z_\alpha \sum_{j=1}^{N} \sigma_{ij} x_j^* \bigg/ \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} \sigma_{ij} x_i^* x_j^*}$.

A couple of observations on the adjustment quantity, a_i^*, are worth discussing. First of all, the magnitudes of adjustments vary potentially from farm to farm and depend on the acreage enrolled on all the farms in the purchase. Secondly, as discussed earlier, if the aggregator is not concerned about whether the total realized offset is greater or smaller than its expected value, then $a_i^* = 0$, and no adjustment is taking place.

A third observation is that, in contrast with the total expected offset being *always discounted* (for $\alpha > 0.5$), the farm-specific per acre expected offsets may be either discounted or adjusted upward in obtaining the solution of the aggregator's problem. Indeed, if the offsets from different farms are positively correlated ($\sigma_{ij} > 0, i \neq j$), then $a_i^* > 0$ for all i; that is, per acre expected benefits are being *discounted* for all the farms in the purchase. However, if the offsets from some fields are negatively correlated, it is possible that the adjustment quantity a_i^* is negative for some farms. To illustrate, consider problem (4) with $N = 2$, $(\overline{b}_1, \overline{b}_2) = (2,1)$, $(c_1, c_2) = (1,1)$, $(\overline{x}_1, \overline{x}_2) = (2,1)$, $\sigma_{11} = \sigma_{22} = 1$, $\sigma_{12} = -0.8$, $C = 2.5$, and $\alpha = 0.99$. The solution to this problem is given by $(x_1^*, x_2^*) = (1.5, 1)$, with the total expected offset, $x_1^* \overline{b}_1 + x_2^* \overline{b}_2 = 4.00$, discounted by $A^* = 2.14$ (see equation (3)). Yet on the per acre basis, only the expected offset of the first farm is discounted ($a_1^* = 1.77$), while that of the second farm is adjusted upward ($a_2^* = -0.50$).

The next section presents an empirical application of the model to the analysis of the expected offset discounting for a hypothetical carbon purchase project in an agricultural production area in the United States.

Empirical Application

The empirical study region, as shown in Figure 1, is the Upper Iowa River Basin, defined as Watershed 7080207 by the U.S. Geological Survey (Seaber, Kapinos, and Knapp 1987). We investigate a hypothetical carbon project that pays farmers for retiring land from crop production and placing it under permanent grass cover in the Conservation Reserve Program (CRP). We consider the uncertainty of offsets resulting from uncertainty in weather, which is known to significantly affect carbon sequestration of CRP (Bruce et al. 1999; Follett et al. 2001; Paustian et al. 2001).

The basic data for simulations come from the 1997 National Resources Inventory (NRI) (Nusser and Goebel 1997). Each NRI point is treated as representing a farm with a size equal to the number of acres represented by the point (the NRI expansion factor).
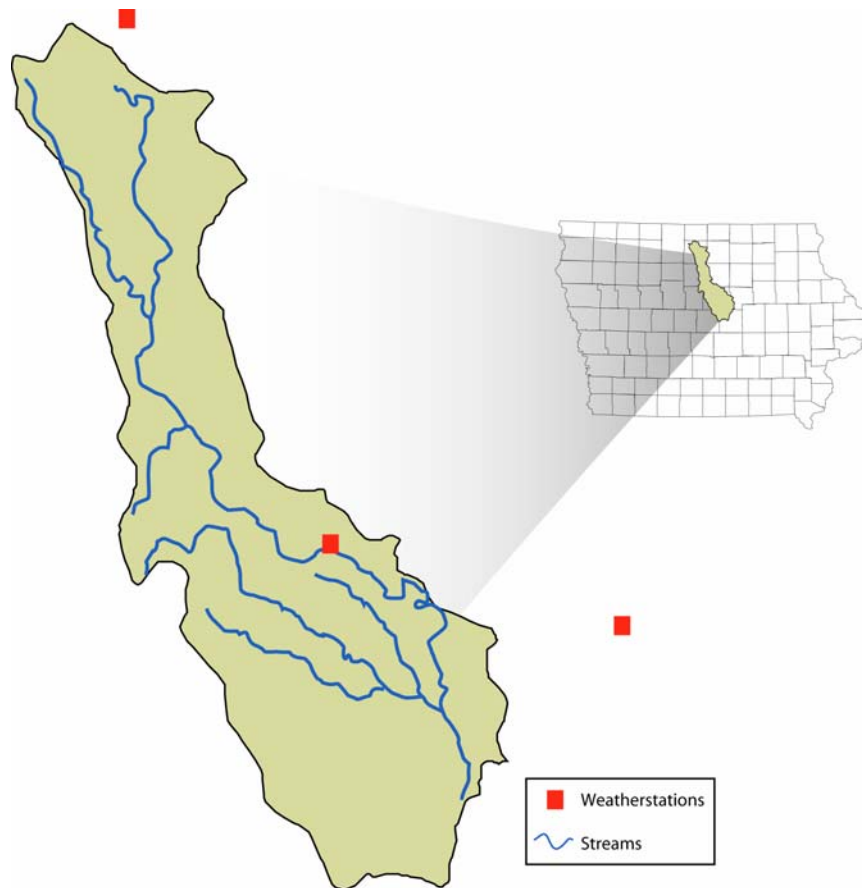
FIGURE 1. Upper Iowa River Basin and the location of weather stations

Some $N = 346$ NRI data points in the basin representing 693,400 acres of cropland are used for the analysis. The estimates of opportunity costs of retiring land from production, c_i, come from Kurkalova, Burkart, and Secchi (2004), who followed the approach of Smith (1995) to measure the opportunity cost of land retirement via cropland cash rental rates. Given that the area is a part of prime agricultural land, it is not surprising that the costs of land retirement are very high, averaging over $130 per acre, as shown in Table 1.

The empirical distributions of offsets, b_i, are obtained at each data point using the EPIC (Environmental Policy Integrated Climate) simulation model (Williams 1990) as follows. First, we use EPIC to generate 50 random weather patterns from the distribution of weather patterns as recorded by the three weather stations in the region. Next, we run 100 30-year simulations at each data point: 50 assuming conventional tillage practices

TABLE 1. Data summary, 346 NRI points

Variable	Notation	Sample Min	Sample Average	Sample Max
Expected carbon offset (mt C per acre)	$\overline{b}_i$	0.014	0.643	2.004
Cost of retiring land from production ($ per acre)	c_i	81.7	130.5	188.6
NRI expansion acres	$\overline{x}_i$	100	2004	3200
Variance of carbon offset (mt C squared per acre squared)	σ_{ii}	$0.030*10^{-3}$	$2.493*10^{-3}$	$86.055*10^{-3}$

and 50 assuming land retirement. Then, we compute 50 estimates of carbon sequestration potential as the difference in soil carbon content after 30 years under land retirement and that under tillage, divided by 30, each time pairing the simulations corresponding to the same weather pattern. Finally, the resulting 17,300 estimates (346 points times 50 weather patterns) are used to compute sample means $\overline{b}_i$, variances σ_{ii}, and covariances σ_{ij}, $i, j = 1,...,346$. The average of the expected per acre offsets in the sample, 1,587 kg C ha^{-1} yr^{-1}, compares favorably with the estimates for this region (Follett et al. 2001; Paustian et al. 2001). Summary statistics on the data used in the simulations are given in Table 1.

Given the data on c_i, $\overline{b}_i$, σ_{ii}, and σ_{ij}, $i, j = 1,...,346$, the aggregator's problem (4) is solved for three levels of budget C, $5 million, $10 million, and $15 million, correspond-ing to enrollment in CRP of 5.9 percent, 11.4 percent, and 16.8 percent of the cropland under consideration, respectively. For each of the budget levels, three confidence levels, $\alpha = 0.90$, 0.95, and 0.99, are analyzed. For comparison purposes, we also report results for the case of $\alpha = 0.50$, corresponding to maximizing total expected offset (and no discounting).

Results

To simplify comparisons across budgets and confidence levels, the estimated ex-pected offset discounting is reported in Table 2 in relative terms, that is, as a percentage of the corresponding expected offset. Thus, the total expected offset discount is reported

TABLE 2. Simulations results

Budget (Million $)	5				10				15			
Confidence Level, α	**0.50**	**0.90**	**0.95**	**0.99**	**0.50**	**0.90**	**0.95**	**0.99**	**0.50**	**0.90**	**0.95**	**0.99**
Carbon claimable (1,000 mt)	61.8	60.0	59.5	58.5	109.3	106.1	105.3	103.9	152.6	147.5	146.3	144.2
Total expected carbon discount (%)	0	2.9	3.8	4.7	0	2.5	3.3	4.4	0	2.9	3.5	4.7
Per acre expected carbon discount (%)												
Minimum	0	0.9	1.2	2.0	0	1.1	1.5	-0.5	0	0.1	-0.1	-0.4
Average	0	2.8	3.5	5.0	0	2.5	3.2	4.2	0	2.7	3.2	4.5
Maximum	0	11.6	14.9	17.5	0	9.5	12.2	17.2	0	13.1	15.1	18.8
Break-even carbon price ($ per mt)	80.9	83.3	84.0	85.5	91.5	94.3	95.0	96.2	98.3	101.7	102.5	104.0
Payment for discounting (% of budget)	0	3.6	4.7	6.5	0	3.4	4.3	5.9	0	4.2	5.1	6.9

as $A^* \Big/ \sum_{i=1}^{N} \overline{b}_i x_i^*$, and the per acre expected offset discount is reported as $a_i^* \big/ \overline{b}_i$. The results of estimation suggest that weather uncertainty as simulated is consistent with the total expected carbon discounting in the range of 2.5 percent to 4.7 percent. Interestingly, the relative magnitude of discounting is fairly consistent across budgets for a given confidence level. For example, when offset target is to be achieved with the confidence level of $\alpha = 0.99$, the total expected offset discounting was found to vary from 4.4 to 4.7 percent.

As expected from the simple numerical example presented earlier, the per acre expected offset adjustments vary widely with the minima being negative for some budgets and confidence levels and the maxima being as high as almost 19 percent. Nevertheless, the average per acre discounts are found to be close to the total expected offset discounts.

Results of estimation suggest that purchasing carbon offsets from farmers with land enrolled in a CRP-like program is profitable for the aggregator at prices beginning at $80.9 per metric ton of carbon offset. Note, however, that because the discounting increases with the increasing confidence level, the higher total offset confidence levels require higher break-even offset prices. This implies that economic feasibility of sequestration in agricultural soils should be addressed with the confidence levels taken into account. For example, if the offset price is set at $102, purchasing 0.147 million metric tons of offset claimable with the confidence level of 90 percent is profitable in this area. But if the confidence level for the offsets were to increase to 95 percent, purchasing that quantity of offsets in this area is no longer profitable. Thus, ignoring the confidence levels may lead to unrealistically optimistic estimates of economic feasibility of carbon sequestration in agricultural soils.

To monetize the effect of offset discounting in an alternative way, we estimate the additional expenses the aggregator incurs because of purchasing the claimable offset $B^* = \sum_{i=1}^{N} \overline{b}_i x_i^* - A^*$ with a specified confidence level as opposed to purchasing the same offset B^* with the confidence level $\alpha = 0.50$, which does not involve discounting. These additional expenses expressed as a percentage of the budget are reported as "payment for discounting" in Table 2. We found that a sizable share of the budget, from 3.4 to 6.9 percent, may be required to make sure that the total offset is claimable with the specified confidence level.

Concluding Comments

The study presents a model of discounting expected carbon sequestration offsets for uncertainty and estimates that weather variability is consistent with up to 5 percent discounting of expected offsets from retiring land from agricultural production in the Upper Iowa River Basin for the budget levels of $5 to $15 million and offset confidence levels of 90 to 99 percent. We found that nearly 7 percent of the budget may be used exclusively to ensure the specified confidence levels of the offsets. The results underscore the importance of incorporating uncertainty and offset confidence levels in the economic assessments of carbon sequestration potential of agricultural soils. Ignoring the uncertainty may lead to overly optimistic conclusions about economically feasible carbon sequestration levels.

While the numerical estimates of the optimal discounting levels and costs may not be immediately transferable to other regions and farming practices, the modeling framework presented can be applied to study the effects of other sources of offset uncertainty. A particularly fascinating extension of this work would be to model and estimate the discounting due to uncertainty about the permanence of the offsets. In this case, the assumption on normality of the distributions of farm-level offsets would probably have to be replaced with that of a more suitable distribution, thus requiring alternative derivation or estimation of the certainty equivalent of the probabilistic definition of offset target.

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