The Dynamics of Carbon Sequestration and Alternative Carbon Accounting, with an Application to the Upper Mississippi River Basin

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Abstract: Carbon sequestration is a temporal process in which carbon is continuously being stored/released over a period of time. Different methods of carbon accounting can be used to account for this temporal nature, including annual average carbon, annualized carbon, and ton-year carbon. In this paper, starting by exposing the underlying connections among these methods, we examine how the comparisons of sequestration projects are affected by these methods and the major factors affecting them. We explore the empirical implications for carbon sequestration policies by applying these accounting methods to the Upper Mississippi River Basin, a large and important agriculture area in the United States. We find that the differences are significant in terms of the location of land that might be chosen and the distribution of carbon sequestration over the area, although the total amount of carbon sequestered does not differ considerably across programs that use different accounting methods or different values of the major factors.

Keywords: annual average carbon, annualized carbon, carbon sequestration, ton-year carbon.

JEL Classification: Q20, Q25

1 Introduction

Carbon sequestration through land use changes and forestry has been the focus of considerable attention in the climate change literature because of its potential as a cost-effective mitigation strategy. With the Kyoto Protocol becoming a binding treaty, countries may have further incentives to incorporate it into their greenhouse gas management plans. Carbon sequestration is a temporal process that removes carbon from the atmosphere either evenly or unevenly over time: the amount of carbon removal is larger in some periods than in others. Negative sequestration, that is, carbon release into the atmosphere is also possible over some time intervals even though a project has overall positive sequestration. In order to properly assess different sequestration projects, it is critical that this temporal attribute be properly accounted for. In this paper, we examine some of the important issues related to carbon accounting and its policy implications when sequestration becomes part of the climate change mitigation portfolio.

In reporting the amount of carbon that has been sequestered in a project, several accounting methods and their variations have been used or proposed in the literature, including the annual average carbon, the annualized carbon, and ton-year carbon. Simply speaking, the annual average carbon, the most widely used accounting method, is the sum of total carbon sequestered over a fixed period of time divided by the length of the period. To reflect our preference for benefits that have occurred earlier, the annualized carbon accounting method discounts carbon sequestered later. Although new relative to annual average carbon, annualized carbon (or its variation, the present discounted value of carbon) has been employed by many studies, including Adams et al. (1999), Plantinga et al. (1999), and Stavins (1999). A third accounting method, the ton-year carbon, takes into account the duration of carbon kept outside of the atmosphere. Several studies (e.g., Watson et al., 2000; Moura-Costa and Wilson, 2000) have analyzed this method with an emphasis on how it facilitates the comparison among projects that sequester (or release) carbon for different lengths of time.

Different projects may show up as the favorable choices when different accounting methods are used. Even under the same accounting method, the ranking of projects may differ, as the value of some factors varies. The first factor is the project duration. There might be some natural choices for the value of this factor, for example, the saturation point, which is the length of time needed for a carbon pool to reach equilibrium. Given that there may be different carbon pools in a single project (let alone in multiple projects), the use of saturation point may result in (a) different durations in different projects and (b) a somewhat subjective decision on which, if any, carbon pool's saturation point to use. In fact, different durations of projects have been employed in the literature to suit the underlying nature of the analyses. For example, Stavins (1999) used a period of 90 years to allow at least one rotation of each project species; Parks and Hardie (1995) limited their study to the life of a temperate forest; and Adams et al. (1999) chose a 50-year period to investigate the costs of sequestration through both afforestation and improvement in forest management.

The effect of the choice of project durations is largely determined by the path of a sequestration project (i.e., distribution of carbon sequestration over time), which is the second factor we are going to explore. Obviously, an accounting method that gives more weight to early sequestration will favor a project that sequesters carbon in relatively early periods. Although seldom discussed in the literature on the cost of sequestration, the effects of different mitigation paths have been extensively debated in the more general climatic change literature (see Wigley et al., 1996 and Ramakrishna, 1997). Some have argued that delaying abatement may be costly because there is socioeconomic inertia in the energy system and the process of climate change is difficult to reverse. If earlier carbon sequestration is valued more, then we may prefer one sequestration project over another even if both projects can sequester the same amount of carbon (undiscounted sum) at the same amount of cost over the same period of time. To take into account the timing of carbon uptake, discounting can be used.

The discount rate is the third factor that we are going to discuss. Instead of sensitivity-type analysis, we examine how the discount rate interacts with sequestration paths and project durations to affect the results of sequestration policies. The advantage of discounting is that it can reflect preferences for early carbon reduction and allow us to focus on some summary measures (e.g., annualized carbon) without being too concerned about the paths of sequestration. However, discounting also brings its own complications because, as we illustrate, a different discount rate may favor a different sequestration activity and, even at the same discount rate, different projects may become the favorable choice as project durations vary.

Some studies have started investigating the issue of accounting for time in climate mitigation through carbon sequestration. The differences of alternative accounting methods and the factors affecting them are discussed in the special report on *Land Use, Land-Use Change and Forestry* by the Intergovernmental Panel on Climate Change (IPCC) (Watson et al., 2000, Chapters 2 and 5). Fearnside et al. (2000) indicated that temporal issues will be key factors in determining whether efforts to mitigate global warming will include carbon sinks and which sequestration activities should be given priority. They identified ton-year carbon accounting as a mechanism to compare sequestration of different durations. They also showed that discounting can strongly influence economic decisions. Tipper and De Jong (1998) carefully described the accounting methods that we analyze in this paper and discussed their advantages and disadvantages. They also applied their discussions to a project in Mexico.

Building on previous research, we contribute to the literature by (i) investigating how the comparisons of the accounting methods are affected by three factors (project durations, discount rate, and carbon sequestration paths) and how the factors interact with each other, and (ii) applying the analysis to a major agricultural area in the United States and demonstrating the different outcomes of policies based on different accounting methods or different values of the factors. We start by describing the accounting methods and their underlying connections in the next section. Then in sections 3-4 we analyze the effects of the three factors. The empirical application is provided in section 5. The last section gives concluding comments.

2 The alternative accounting methods

In order to understand the underlying connections between the accounting methods, we begin with the following framework. Consider a program with a funding of M, which selectively enrolls fields from a total of N agricultural or forest fields to sequester carbon from time 0 to time T. We call T the project duration. Each piece of land is enrolled for some carbon sequestration practices during this period of time. The size of field n is denoted as A_n, where n is the index of a field. Carbon sequestered at time t by a unit of land on field n is denoted as $x_n(t) \geq 0$. Denote the cost of enrolling a unit of land from field n as $p_n(t)$, which is the profit forgone and/or establishment expenditures due to the adoption of carbon sequestration activities. Given that our focus is on carbon accounting, for simplicity we assume that the benefit of carbon sequestration for mitigating climate change is constant over time, denoted as b for any t for each unit of carbon sequestered.

Suppose the policymaker's problem is to choose a_n for each field to maximize the present discounted value (PDV) of the benefit from sequestration over the project duration, i.e.,

$$\max_{a_n} \quad \sum_{n=1}^{N} \int_0^T \int_t^T b \cdot a_n \cdot x_n(t) \cdot e^{-rs} ds dt \tag{1a}$$

$$s.t. \quad \sum_{n=1}^{N} a_n \int_0^T e^{-rt} p_n(t) dt = M, \tag{1b}$$

$$0 \leq a_n \leq A_n, \tag{1c}$$

where r is the discount rate for the policymaker. In the objective function, the inner integration represents the overall benefit from the carbon sequestrated at time t in field n. The benefit starts accruing from the time of sequestration (t) and lasts until the end of the project duration (T). The outer integration essentially sums up the benefit of carbon sequestered at each point of time over $[0, T]$. The budget constraint, (1b), indicates that the total payment over $[0, T]$ for all enrolled fields is equal to the available funding.[1] It is important to note here that all enrollment occurs at time 0 and a_n does not change with time. Because of the reversibility of carbon sequestration, it is important for a policy to enroll a farmer for a relatively long period of time. Also for the same reason of non-permanence, it is important to take into account the duration of benefits from sequestration.

Using λ as the multiplier for the budget constraint, the solutions to (1) can be written as follows:

$$a_n^* = \begin{Bmatrix} A_n \\ 0 \\ a^* \end{Bmatrix} \quad \text{if} \quad bX_n \begin{Bmatrix} > \\ < \\ = \end{Bmatrix} \lambda^* \int_0^T e^{-rt} p_n(t)dt; \tag{2}$$

$$\text{where} \quad X_n \equiv \int_0^T x_n(t) \int_t^T e^{-rs} ds dt; \quad \text{and} \tag{3}$$

$a^* = \left(M - \sum_{\{i:\, a_i^* = A_i\}} a_i^* \int_0^T e^{-rt} p_i(t)dt \right) \Big/ \int_0^T e^{-rt} p_n(t)dt$. Intuitively, λ^* is the shadow cost of funding. The left-hand side of the conditions in (2) represents the total PDV of benefit from field n, while the right-hand side represents the PDV of costs from field n for carbon sequestration over the project duration. Whether to enroll field n depends on whether the PDV of benefit is greater than the PDV of cost. If benefit is less than cost, then the field will not be enrolled. On the contrary, a whole field will be enrolled if its benefit is greater than the corresponding cost. When benefit and cost are equal for a field, the area enrolled from the field (a^*) is determined by the price of enrolling the parcel and the funding left after payment for all other parcels with whole-field enrollment.

The term X_n can be considered as a measure of total carbon accumulated on

[1] Another form of resource constraint is the total available land. However, our discussions would mostly stay the same with the use of this constraint.

one unit of field n. In empirical analysis, several important simplifications of X_n are often used, including the sum of carbon, the PDV of carbon, and the ton-year carbon. By dividing a constant (some variation of the length of time), these measures are equivalent to annual average carbon, annualized carbon, and the average ton-year carbon, respectively. We will next define these terms, show their connections with X_n, and highlight the assumptions under each of these measures.

Definition 1 *The sum of carbon sequestration in a unit of land on field n ($\bar{X}_n$) is the simple summation of carbon sequestered over $[0, T]$; and annual average carbon ($\bar{x}_n$) is the sum of carbon sequestered divided by the corresponding period of time; that is,*

$$\bar{X}_n \equiv \int_0^T x_n(t)dt, \quad \textit{and} \quad \bar{x}_n \equiv \frac{\bar{X}_n}{T}. \tag{4}$$

Comparing X_n and $\bar{X}_n$, we know that the latter is derived by setting $r = 0$ and assuming that carbon sequestered at time t only has effect at time t (as opposed to over the period from t to T). Thus, the sum of carbon does not take into account the fact that, relative to carbon sequestered later, carbon sequestered earlier provides earlier benefit that is usually valued more and provides benefit for a longer duration.

Definition 2 *The present discounted value of carbon sequestration in a unit of land on field n ($\hat{X}_n$) is the sum of carbon sequestered over $[0, T]$ weighted by a discounting term, e^{-rt}; and the annualized carbon ($\hat{x}_n$) is a constant equal for all time points such that the PDV of this constant is equal to $\hat{X}_n$; that is,*

$$\hat{X}_n \equiv \int_0^T e^{-rt} x_n(t)dt, \quad \textit{and} \quad \hat{x}_n \equiv \frac{\hat{X}_n}{\int_0^T e^{-rt}dt}. \tag{5}$$

Setting $r = 0$ in $\hat{X}_n$, we have $\hat{X}_n = \bar{X}_n$. Also, if we assume that carbon sequestered at time t only has effect at time t, then $X_n = \hat{X}_n$. It may seem unusual to use the PDV of a physical good, carbon, because PDVs are in general calculated for monetary values. In fact, in the model setup (1), only monetary values are discounted. Carbon discounting results from the discounting of the benefit provided by future sequestration.

Definition 3 *The ton-year carbon sequestration in a unit of land on field n ($\tilde{X}_n$) is the sum of carbon sequestered over [0, T] weighted by the length of the period lasting from the time carbon is sequestered until the end of the project duration,*[2] *and average ton-year carbon ($\tilde{x}_n$) is a constant equal for all time points such that the ton-year carbon of this constant is equal to $\tilde{X}_n$; that is,*

$$\tilde{X}_n \equiv \int_0^T \int_t^T x_n(t) ds dt, \quad \text{and} \quad \tilde{x}_n = \frac{\tilde{X}_n}{\int_0^T \int_t^T 1 ds dt}. \tag{6}$$

It is easy to see that the only difference between $\tilde{X}_n$ and X_n is the discounting factor: specifically, in the former, r is set to 0. One difference between $\tilde{X}_n$ and $\hat{X}_n$ (or $\bar{X}_n$) is that the former takes into account the duration of benefit while the latter does not. It is interesting to note that some researchers have proposed a conversion factor between 1 ton-year carbon of sequestration and 1 ton of carbon emission reduction, which is estimated to be about 0.0182 (Moura-Costa and Wilson, 2000; and Tipper and De Jong, 1998).

From their definitions, it is clear that the accounting methods can be very different mainly due to some factors: r, T, and $x_n(t)$. The sequestration path, $x_n(t)$, is given for a fixed field with specified land use practices except for variations caused by natural uncertainties. As we discussed in the introduction, the choice of T is not as obvious as it first appears. When projects have different sequestration paths, the choice of r and T may affect the ranking of projects no matter which carbon

[2] Although in our analysis ton-year carbon does not incorporate discounting, one might modify the approach to include discounting.

accounting method is used. As a result, different projects may be included in carbon sequestration policies, which in turn may affect the overall outcome of policies.

3 The effects of discounting under different carbon paths

If carbon sequestration is linear (i.e., constant over time), say, $x_n(t) = x$, then it is easy to show that all three accounting methods will be equivalent in the sense that the annual average carbon, the annualized carbon, and the average ton-year carbon will have exactly the same value. In such cases, the choice of projects is not affected by the choice of accounting methods. However, carbon sequestration is usually non-linear. For example, carbon sequestration by afforestation is largely determined by the accumulation of biomass, which is generally known to be slow at the beginning, faster in the midterm, and then slow again near maturity. The duration of each stage could range from a few years to more than a hundred years, depending on the timber species. Two examples are illustrated in Figure 1, which is based on Richards et al. (1993). A similar process also exists for carbon sequestration by switching from conventional tillage to conservation tillage (Lal et al., 1998).

When linearity is not satisfied, two fields may have quite different annualized carbon even if they have the same undiscounted annual averages of carbon and the same r and T are used. In other words, $\hat{x}_n - \hat{x}_m$ may be large in absolute value even if $\bar{x}_n - \bar{x}_m$ is zero. The disparity between $\hat{x}_n - \hat{x}_m$ and $\bar{x}_n - \bar{x}_m$ is affected by the curvature of $x_n(t)$ and $x_m(t)$, since $\hat{x}_n$ and $\hat{x}_m$ discount later sequestration while $\bar{x}_n$ and $\bar{x}_m$ do not. If we view carbon sequestration $x_n(t)$ as the weight attached to the corresponding time t, then $x_n(t)$, upon appropriate normalization, can be viewed as the probability density function of t. This view of $x_n(t)$ enables utilization of well-known results in the literature on finance and risk. Before invoking any result, we present the definitions of two concepts.

Definition 4 *Let $F^i(y)$ and $F^j(y)$ be two cumulative distribution functions (cdf's) of a random variable $y \in [\underline{y},\ \bar{y}]$. (i) $F^i(y)$ first-order stochastically dominates (FOSD) $F^j(y)$ if*

$$\int_{\underline{y}}^{\bar{y}} \phi(y) dF^i(y) \geq \int_{\underline{y}}^{\bar{y}} \phi(y) dF^j(y) \tag{7}$$

for any non-decreasing function $\phi(y)$. (ii) $F^i(y)$ second-order stochastically dominates (SOSD) $F^j(y)$ if (7) *holds for any non-decreasing concave function $\phi(y)$.*

We can show that $F^i(y)$ FOSD $F^j(y)$ if $F^i(y) \leq F^j(y)$, for any $y \in [\underline{y},\ \bar{y}]$. Also, given the same mean, if Y has larger variability under $F^j(y)$ than under $F^i(y)$ then $F^i(y)$ SOSD $F^j(y)$. Loosely speaking, FOSD compares the means (levels) of two distributions while SOSD, in addition, compares their spread over the domain of a random variable. Suppose the two cdf's are the distributions of random net returns associated with two investment projects. If $F^i(y)$ FOSD $F^j(y)$, that is, higher returns are more likely to occur under $F^i(y)$ than under $F^j(y)$, then the former will be preferred over the latter by any investor who values higher returns more. If $F^i(y)$ SOSD $F^j(y)$, then the former will be preferred over the latter by risk-averse investors because net returns from the former tend to be less variable and/or higher in all states of nature.

In our context, we can construct a cdf as follows. Define

$$F^i(t) = \frac{\int_0^t x_i(s) ds}{\int_0^T x_i(s) ds}, \quad i = 1, 2, ..., N. \tag{8}$$

Although $F^i(t)$ satisfies all the conditions required for a cdf, different probability densities are only artificially attached to different values of t since t is *not* a random variable. Based on $F^i(t)$, we next provide a proposition on the comparison of carbon paths based on annual average carbon and annualized carbon.

Proposition 1 *Given $\bar{x}_n = \bar{x}_m$, if $F^m(t)$ first-order stochastically dominates $F^n(t)$ then $\hat{x}_n \geq \hat{x}_m$ for any $r > 0$; if $F^m(t)$ second-order stochastically dominates $F^n(t)$, then $\hat{x}_n \geq \hat{x}_m$ for $r > 0$.*[3]

A proof is given in the appendix. Intuitively, the probability density artificially given to each value of t is determined by the rate of carbon sequestration. The first-order stochastic dominance by $F^m(t)$ over $F^n(t)$ means that proportionally less carbon is accumulated earlier under path $x_m(t)$ than under path $x_n(t)$. Given that earlier sequestration is valued more (for $r > 0$) in calculating the PDV of a stream of carbon sequestration, the PDV is greater from $x_n(t)$ than from $x_m(t)$; that is, $\hat{X}_n \geq \hat{X}_m$, or equivalently, $\hat{x}_n \geq \hat{x}_m$.

For the paths given in Figure 1, the two pines have about the same annual average carbon, 2.15 tons/year/acre, for the period from year 0 to year 77. Then based on the curvature of the two paths, it is easy to see that $F^m(t)$ first-order stochastically dominates $F^n(t)$ for the same period. So $\hat{x}_n \geq \hat{x}_m$ for any $r > 0$ by Proposition 1. In fact, for the same period and at a 2 percent discount rate, the annualized carbon sequestration for loblolly and ponderosa pines are $\hat{x}_n = 2.62$ and $\hat{x}_m = 1.84$ tons/year/acre, respectively. The difference between $\hat{x}_n - \hat{x}_m$ and $\bar{x}_n - \bar{x}_m$ is about 0.78 tons/year/acre, which accounts for 36 percent of the annual average carbon sequestration.

When there is no FOSD relationship between $F^m(t)$ and $F^n(t)$, the first half of Proposition 1 does not apply. However, if we know that $F^m(t)$ SOSD $F^n(t)$, then we can invoke the second half of the proposition. Graphically, the second-order stochastic dominance of $F^m(t)$ over $F^n(t)$ implies that carbon uptake spreads out

[3] From their definitions, it is clear that FOSD implies SOSD. That is, if $F^m(t)$ FOSD $F^n(t)$, then $F^m(t)$ SOSD $F^n(t)$. Thus, the first part of the proposition is captured in the second part of the proposition. Both are presented here to facilitate discussion.

more evenly over time and/or occurs earlier along path $x_n(t)$ than along path $x_m(t)$ (see Figure 2). Because of discounting, the value of carbon sequestration decreases at an exponential rate, e^{-rt}, and so the annualized carbon is higher for a carbon path with relatively more early carbon sequestration. Thus, we have $\hat{x}_n \geq \hat{x}_m$.

It is important to note that Proposition 1 only applies to some carbon paths since FOSD and SOSD do not completely characterize the relationship between two cdf's. It may happen that neither cdf dominates the other in terms of FOSD or SOSD. In these situations, the comparisons of accounting methods and carbon paths will be more complicated, as illustrated by the following section.

4 The effects of T, r, and carbon sequestration path

In this section, we will explore by illustration how T, r, and sequestration paths affect the accounting methods, focusing on how the comparisons of the accounting methods might be affected by the factors and how the effects of one factor might be influenced by another factor. Tables (1a) and (1b) show annualized carbon sequestration ($\hat{x}_n$) in an acre of afforestation for two species of pines with different r and T. The first row of the tables (with $r = 0$) indicates the effect of different T on the annual average carbon. Instead of $\hat{X}_n$, we use its normalized version $\hat{x}_n$ to make meaningful comparisons because it is hard to make sense of the comparison between carbon sequestered, say, over 20 years and over 50 years, unless we take into account the length of time. The two pines are used as an illustration because of the sharp contrast in their sequestration paths as indicated by Figure 1.

From Tables (1a) and (1b), we can see that for loblolly pine, as T increases, the annualized carbon decreases for all four discount rates shown,[4] while for ponderosa

[4] At $r = 0.15$ for $T > 60$, the change in $\hat{x}_n$ is negligible. This is because r is so high that little is added to the numerator and denominator of (5) as T increases. This is also the case for ponderosa pine.

pine, it first increases and then decreases. Similarly, as r increases, for ponderosa pine the annualized carbon decreases for all four project durations, while for loblolly pine the relationship varies with T. The lack of a specific pattern in the change of annualized carbon in response to the change of T (or r) can be explained by the definition of $\hat{x}_n$ in (5). For any given r, as T increases $\hat{x}_n$ will also increase if $x_n(T) - \hat{x}_n$ (a term in $d\hat{x}_n/dT$) is positive. Intuitively, this implies that if the carbon sequestration rate is higher at T or after T than the annualized sequestration rate over $[0, T]$, then as T increases, $\hat{x}_n$ becomes larger. This is the case when T increases from 30 years to 60 or 90 years for ponderosa pine. On the other hand, if the sequestration rate decreases over time, then the difference of the two terms will be negative and $\hat{x}_n$ will decrease as T increases. This is the case for loblolly pine when T is greater than 30 years or for ponderosa pine when T increases from 90 to 160 years.

Similarly, we can explain the phenomena that, as r increases, $\hat{x}_n$ may increase for one sequestration path but not the other and the trend even varies for the same given path and project duration as in the case of loblolly pine. As r increases, both the numerator, $\int_0^T e^{-rt} x_n(t)dt$, and the denominator, $\int_0^T e^{-rt}dt$, in (5) will decrease. If the former decreases more slowly (quickly) than the latter, then $\hat{x}_n$ will increase (decrease). That is, if $\int_0^T te^{-rt}dt / \int_0^T e^{-rt}dt - \int_0^T te^{-rt}x_n(t)dt / \int_0^T e^{-rt}x_n(t)dt$ is positive (negative), then $\hat{x}_n$ will increase (decrease). The first ratio is essentially the average of t weighted by e^{-rt} and the second ratio is essentially the average of t weighted by $e^{-rt}x_n(t)$. If the rate of sequestration tends to be higher closer to time T, then the second ratio gives relatively more weight to larger t, which implies the difference of the two ratios will be negative and $\hat{x}_n$ will decrease with r.

Intuitively, as r increases, the value of later sequestration will be valued even less, which implies lower annualized carbon if sequestration tends to occur later. This is the case for all listed project durations for ponderosa pine, which has an increasing rate of sequestration for a long period of time (nearly 80 years). For loblolly pine, although sequestration starts to decline around year 20, the rate of sequestration is still relatively high for the period between year 20 and year 30. Thus, over the period from year 0 to year 30, more sequestration occurs relatively later, and so $\hat{x}_n$ decreases as r increases. However, for other T values in Table (1a), more sequestration occurs relatively earlier and so the value of $\hat{x}_n$ increases for low discount rates. At the highest discount rate in the table ($r = .15$), the trend is reversed. The reason is that, at a very large r, the value of e^{-rt} decreases rapidly and so only sequestration that occurs really early matters. This means that the increasing trend in the early years of loblolly pine dominates the decreasing trend later. As a result, $\hat{x}_n$ actually decreases.

By comparing the values in Tables (1a) and (1b), it is obvious that loblolly pine has higher annualized carbon than the ponderosa pine for all T and r except for a very low discount rate and long project duration, that is, ($r = 0$, $T = 90$), and ($r = 0$, $T = 160$). While not shown, it is not necessarily true that, for a given T value, high discount rates always favor one project while low discount rates favor another. More specifically, in order to compare the annualized carbon sequestration along two different paths $x_n(t)$ and $x_m(t)$ for the same duration, we can assess the sign of

$$D(r) \equiv \int_0^T e^{-rt} \left[x_n(t) - x_m(t)\right] dt.$$

From the definition of $\hat{x}_n$ in (5), we know $\hat{x}_n - \hat{x}_m \geq 0$ if and only if $D(r) \geq 0$. If we treat $x_n(t) - x_m(t)$ as the net cash flow of a project, then $D(r)$ is the net present discounted value of this project. The discount rate r such that $D(r) = 0$ is called the internal rate of return (ROR) of a project. The well-known disadvantage of ROR is that it is not unique and that $D(r)$ is not monotone in r. Saak and Hennessy (2001) and Oehmke (2000) identified conditions in which $D(r)$ is monotone in r.

Even when the dividing discount rate such that $D(r) = 0$ is unique, it can change as project duration varies. In the example of the loblolly pine and ponderosa pine, at $T = 160$, the dividing discount rate is about 0.0153; that is, the PDV of carbon sequestration by loblolly pine is larger if $r > 0.0153$. At $T = 90$, the dividing discount rate is about 0.0074, which is smaller than that at $T = 160$. This is because carbon sequestration by loblolly pine almost tapers off to zero for $T > 90$, while sequestration by ponderosa pine is still significant (see Figure 1). Thus, for a project duration longer than 90 years, a higher discount rate is needed in order for the PDV of carbon sequestration by loblolly pine to remain larger.

Tables 2a and 2b show the average ton-year carbon ($\tilde{x}_n$) with different T for the same two pines. As T increases, $\tilde{x}_n$ shows about the same trend as $\hat{x}_n$ with $r = 0$ (which is also $\bar{x}_n$, shown in the first row in Tables (1a) and (1b)). The only difference is in ponderosa pine going from $T = 90$ to $T = 160$: $\tilde{x}_n$ is increasing while $\bar{x}_n$ is decreasing. This can be explained by the following difference in the accounting methods. As T increases, how $\tilde{x}_n$ changes depends on the balance of two effects: the longer duration of early sequestered carbon and the carbon sequestered after T. The first effect is not reflected in $\bar{x}_n$. If too little carbon is sequestered after T, there will be a decreasing pressure on $\tilde{x}_n$. If the increasing effect from the longer duration of early sequestration cannot outweigh this decreasing effect, then $\tilde{x}_n$ decreases, as in the case of loblolly pine for all project durations and ponderosa pine when T increases from 90 to 160. However, if there is enough sequestration after T, combined with the increasing effect of the increased duration of early sequestration, then this means that $\tilde{x}_n$ increases, as in the case of ponderosa pine for $T = 30$, 60, and 90.

5 Implications for sequestration policies

In this section, we examine the policy implications of the accounting methods and the factors affecting them for an important region of the United States, the Upper Mississippi River Basin (UMRB). The UMRB covers 492,000 square kilometers mostly in five states (Illinois, Iowa, Missouri, Minnesota, and Wisconsin) of the central United States. This area is comprised of 131 U.S. Geological Service (USGS) eight-digit watersheds (shown on Figures 3-5) and is dominated by agriculture: cropland and pasture together account for about 67 percent of the total area. Our primary data source is the latest available National Resource Inventory (NRI) (USDA-NRCS, 1997) which provides information on the natural resource characteristics of the land, cropping history, and farming practices across the region. To estimate the environmental benefits, we use the Environmental Policy Integrated Climate (EPIC) model version 3060.[5] EPIC simulations were run for each NRI point in the region (over 40,000 points in total) for the specified project duration.

We consider a green payment type policy; that is, we assume that policymakers pay farmers to adopt conservation practices on their fields to sequester carbon. The conservation practice we consider here is no-till, which has been shown to have carbon sequestration potential (Lal, et al. 1998). We assume that the goal of the policymakers is to maximize the benefit from carbon sequestration as specified in equation (1a) with simplifications as implied by Definitions 1-3 to account for different accounting methods. With a constraint of a given total acreage of land enrolled (specifically, 20 percent of the UMRB cropped area excluding pasture), it is optimal for policymakers to pay for fields with the highest carbon sequestration potential to adopt no-till.

The alternative policy scenarios we consider differ only by the accounting mecha-

[5]EPIC has been tested under a variety of conditions. Additional information concerning EPIC and details concerning model assumptions and data can be found in Feng et al. 2004.

nism used to measure sequestration potential. For example, if sum of carbon is used, then fields with the highest sum of carbon over the project duration will be selected first, regardless of these fields' sequestration potential in terms of ton-year carbon, or the PDV of carbon. Similarly, if ton-year carbon is used, then fields will be ranked by their sequestration potential in terms of ton-year carbon over the project duration and the fields ranked on top will be enrolled into the program, regardless of these fields' sum of carbon or PDV of carbon over the same period.

In the following, we present the results of some pair-wise comparisons of the alternative accounting mechanisms.[6] While these comparisons use a project duration of 20 years, we also illustrate the effects of project duration by comparing policies which rank fields based on 50-year and 20-year sum of carbon, respectively. For most fields, rapid carbon sequestration occurs within the first 20 years after switching to no till and a new soil carbon equilibrium will be reached by the 50th year. However, there is a large degree of heterogeneity due to the variations in crop rotation, soil, and other natural conditions. The differences between the policy scenarios can be illustrated in two ways: the location of fields enrolled and the amount of carbon sequestered. To represent the difference in the location of land enrolled, we first compute, for each 8-digit USGS watershed in the UMRB, the area of all fields that are only enrolled under one policy (y_1) and the area of all fields that are enrolled under both policies (y_2), and then calculate the ratio, $100 * y_1/y_2$. To illustrate the difference between the amount of carbon sequestered under the policy using one accounting method (y_3) and the carbon sequestered under the policy using another accounting method (y_4), we use the percentage difference, that is, $100 * (y_4 - y_3)/y_3$.

Figures 3-5 display these differences: the deeper the color the larger the differ-

[6]To avoid redundancy, only a few pair-wise comparisons are chosen, even though there are potentially many such comparisons.

ence. A few observations can be made based on the maps. First, in terms of either location of land enrolled or carbon sequestered, the difference between the accounting methods using 20-year and 50-year annual average carbon appears to be the largest and the difference between ton-year accounting and PDV accounting methods the smallest (see Figure 3 versus Figure 4). This indicates that many fields that have relatively high annual average carbon over 20 years do not have high annual average carbon over 50 years. On the other hand, a field that has high ton-year carbon also tends to have high PDV of carbon over the same period, probably because both accounting methods give more weight to early sequestration (although for different reasons and in different ways).

Second, the differences are larger when expressed in the form of the location of land enrolled than in the form of carbon sequestered, as illustrated by the contrast between maps on the left and the corresponding maps on the right in Figures 3-5. This is mainly because (1) the difference between the fields in terms of carbon sequestration potential is small, and (2) the percentage differences are based on the same accounting method in order to make the comparisons meaningful, even though the policies are based on different accounting methods. Third, for all of the comparisons, the differences tend to concentrate on Iowa and southern Minnesota where most land is enrolled. Fourth, in term of the magnitude of difference, 73 percent (40 percent) of the watersheds have a difference larger than 25 percent (50 percent) in terms of the location of fields in the comparison between the 20-year and 50-year annual average carbon, the comparison showing the largest differences (see Figure 3A). Interestingly, in terms of the total sum of carbon sequestered over the whole UMRB, the difference between the policies is almost negligible (and so not presented here). It is up to policymakers to decide in the actual design of policies (a) the importance of the aggregate sequestration potential, and (b) the importance of heterogeneity in terms of geographical location.

6 Conclusions

Because of the dynamics of carbon sequestration, the accounting for time in the estimate of carbon storage is critical in assessing sequestration projects and in comparing carbon sinks and other climate change mitigation options. The time dimension of carbon sequestration is accounted for in different ways in the different accounting methods discussed in this paper. In analyzing sequestration options, the choice of accounting mechanisms tends to be study specific. The annual average carbon method and a default project duration of 20 years are currently used in IPCC's good practice guidance on inventorying and reporting greenhouse gas emissions and removals in "cropland remaining cropland" and "land converted to cropland" (Penman et al., 2003). Given that different projects might be favored under different accounting mechanisms, regions/countries may advocate an accounting system that is most suitable for their sequestration projects. For example, regions with relatively early sequestration may advocate annualized carbon because of its preferential treatment for early sequestration.

The quantity of carbon sequestered is not the only consequence of the use of alternative accounting systems. In fact, in our empirical analysis, no significant difference is found in terms of total amount of carbon sequestered among policies using different accounting mechanisms. Instead, we find that quite different geographical areas will benefit under the policies. Our results may be specific to our study region and the sequestration activities considered. However, this points out a possibility that governments can choose an accounting mechanism to meet other policy goals such as income support for a certain group of people. Of course, how much freedom a national government has in choosing accounting methods depends on the extent of international coordination.

Appendix: Proof for Proposition 1

Note that $\phi(t) = -e^{-rt}$ is an increasing function for any $r > 0$. Thus, if $F^m(t)$ FOSD $F^n(t)$, then by (7) we have

$$\int_0^T (-e^{-rt}) dF^m(t) \geq \int_0^T (-e^{-rt}) dF^n(t), \quad \forall \;\; r > 0. \tag{A-1}$$

Plugging in (8) and rearranging, we obtain

$$\int_0^T \frac{e^{-rt} x_m(t)}{\int_0^T x_m(s) ds} dt \leq \int_0^T \frac{e^{-rt} x_n(t)}{\int_0^T x_n(s) ds} dt, \quad \forall \;\; r > 0.$$

Given $\bar{x}_n = \bar{x}_m$, we know $\int_0^T x_m(s) ds = \int_0^T x_n(s) ds$. Thus we can drop them from both sides of the above inequality. Then, dividing both sides by $\int_0^T e^{-rt} dt$, we have

$$\hat{x}_m \leq \hat{x}_n, \quad \forall \;\; r > 0.$$

Similarly, since $\phi(t) = -e^{-rt}$ is non-decreasing and concave for any $r > 0$, (A-1) still holds if $F^m(t)$ SOSD $F^n(t)$. The second half of the proof follows in a way similar to the proof for the first half of Proposition 1.

References

Adams, D.M., R.J. Alig, B. A. McCarl, J.M. Callaway, and S.M. Winnet. 1999. Minimum Cost Strategies for Sequestering Carbon in Forests. Land Economics 75(3): 360-374.

Fearnside, P.M., D.A. Lashof, and P. Moura-Costa. 2000. Accounting for Time in Mitigating Global Warming through Land-Use Change and Forestry. Mitigation and Adaptation Strategies for Global Change 5: 239-270.

Feng, H., L.A. Kurkalova, C.L. Kling, and P.W. Gassman. 2004. Environmental Conservation in Agriculture: Land Retirement versus Changing Practices on Working Land. Center for Agricultural and Rural Development, Iowa State University, 04-WP 365.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effects. Chelsea, MI: Sleeping Bear.

Moura-Costa, P., and C. Wilson. 2000. An Equivalence Factor Between CO2 Avoided Emissions and Sequestration—Description and Application in Forestry. Mitigation and Adaptation Strategies for Global Change. 5: 51-60, 2000.

Oehmke, J.F., 2000. Anomalies in Net Present Value Calculations. Economics Letters 67: 349–351.

Parks, P.J., and I.W. Hardie. 1995. Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests. Land Economics 71(1): 122-136.

Penman, J., M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, and F. Wagner. 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Published by the Institute for Global Environmental Strategies (IGES) for The Intergovernmental Panel on Climate Change (IPCC).

Plantinga, A.J., T. Mauldin, and D.J. Miller. 1999. An Econometric Analysis of the Costs of Sequestering Carbon in Forests. American Journal of Agricultural Economics 81(November): 812-824.

Ramakrishna, K. 1997. The Great Debate on CO2 Emissions. Nature 390(20): 227-228.

Richards, K.R., R.J. Moulton, and R.A. Birdsey. 1993. "Costs of Creating Carbon Sinks in the U.S." *Energy Conversion Management.* 34(9-11): 905-912.

Saak, A., and D.A. Hennessy. 2001. Well-Behaved Cash Flows. Economics Letters 73: 81– 88

Stavins, R.N. 1999. The Cost of Carbon Sequestration: A Revealed Preference Approach. American Economic Review 89(4): 994-1009.

Tipper R. and B.H. De Jong. 1998. Quantification and Regulation of Carbon Offsets from Forestry: Comparison of Alternative Methodologies, with Special Reference to Chiapas, Mexico. Commonwealth Forestry Review 77(3): 219-228.

United States Department of Agriculture – National Resource Conservation Service (USDA-NRCS). 1997. National Resource Inventory: data files. http://www.nrcs.usda.gov/technical/nri/1997.

Watson, R.T., I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, and D.J. Dokken (Eds.). 2000. Land Use, Land-Use Change, and Forestry. Special Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, UK.

Wigley, T.M.L., R. Richels, and J.A. Edmonds. 1996. Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations. Nature 379(18): 240-243

Table 1. Annualized carbon sequestration ($\hat{x}_n$) (tons/acre/year)[7]

(a) Loblolly pine

	T=30	T=60	T=90	T=160
r=0	3.562	2.621	1.868	1.065
r=.02	3.485	2.885	2.479	2.163
r=.05	3.333	3.083	2.979	2.948
r=.15	2.704	2.700	2.700	2.700

(b) Ponderosa pine

	T=30	T=60	T=90	T=160
r=0	1.369	1.992	2.224	1.940
r=.02	1.261	1.731	1.889	1.878
r=.05	1.101	1.365	1.418	1.415
r=.15	0.694	0.713	0.713	0.713

Table 2. Average ton-year carbon ($\tilde{x}_n$) (tons/acre/year)[8]

(a) Loblolly pine

T=30	T=60	T=90	T=160
3.338	3.130	2.607	1.754

(b) Ponderosa pine

T=30	T=60	T=90	T=160
1.009	1.568	1.887	2.058

[7] For easy reference: 1 acre=0.40 hectare, 1 ton=0.91 tonne, and 1 ton/acre=2.24 tonne/hectare.

[8] Had we used discounting in our definition of ton-year carbon, we could obtain tables like Tables (1a) and (1b) with similar results. Results are available from the author upon request.

Figure 1. The path of loblolly and pondorosa pines

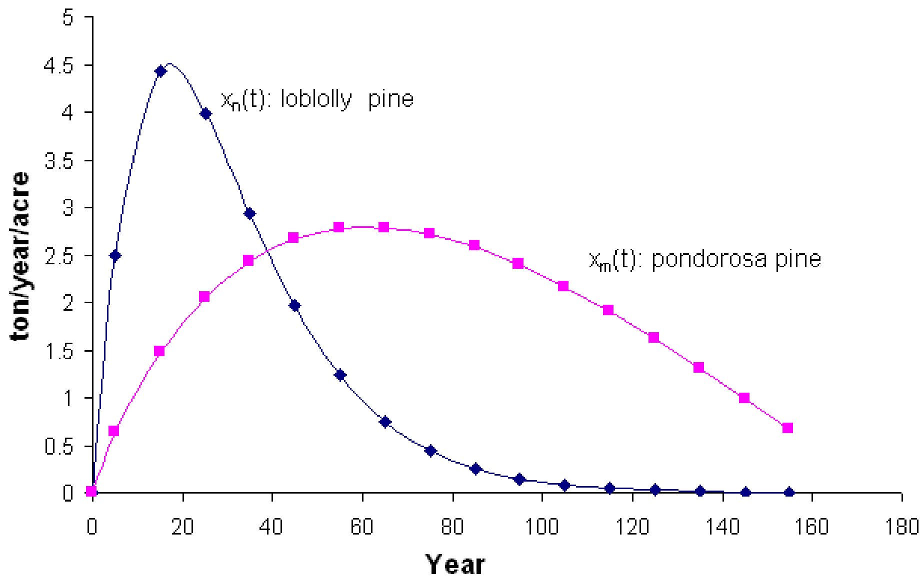


Figure 2. Comparison of carbon paths

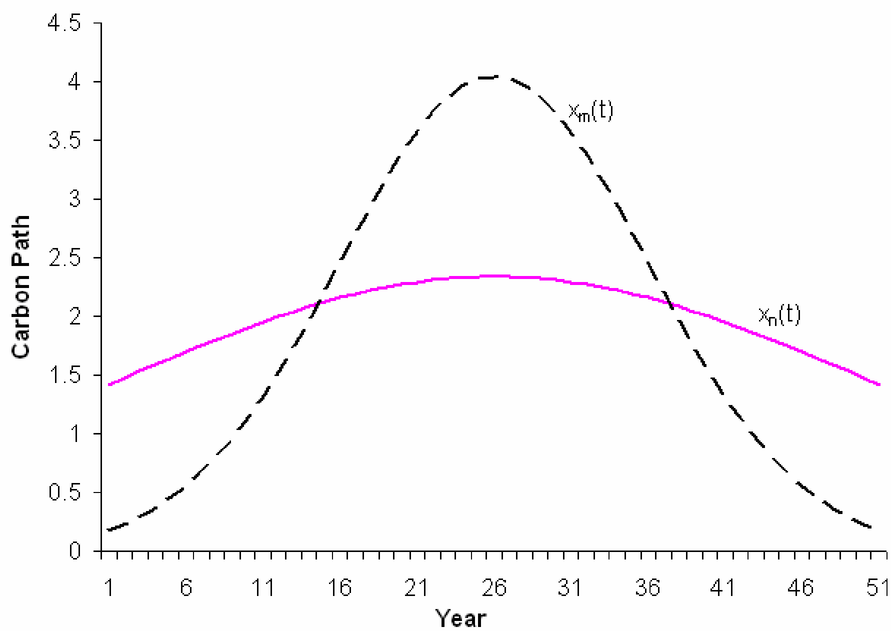
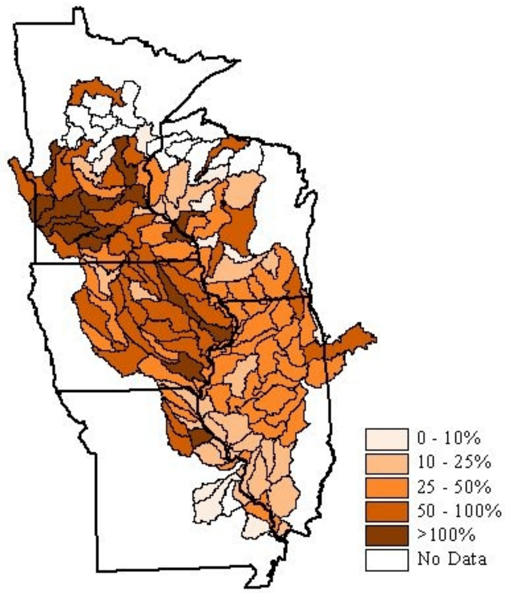


Figure 3. Project duration of 20 years vs project duration of 50 years[9]

A. Difference in location of land enrolled



B. Difference in carbon sequestered

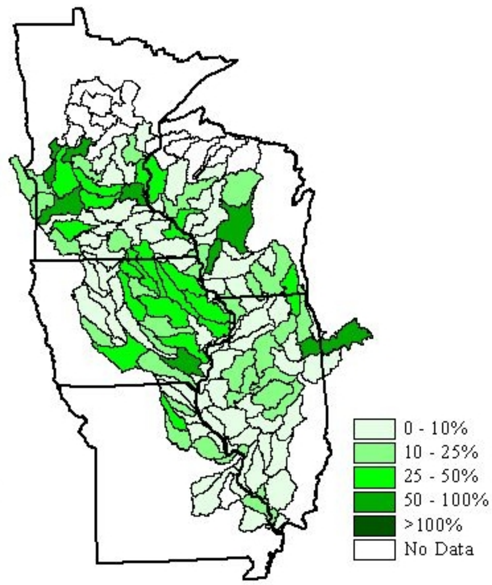
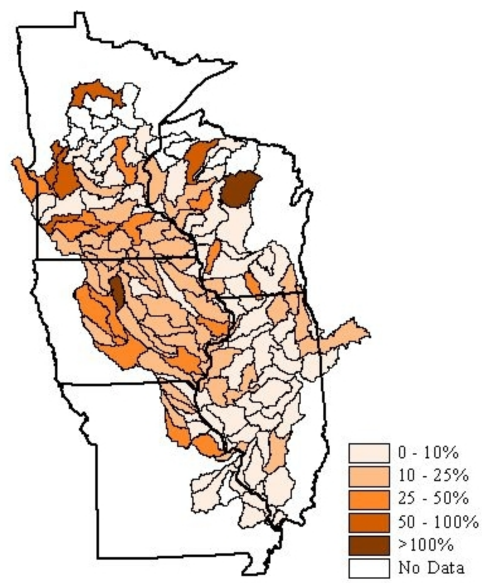
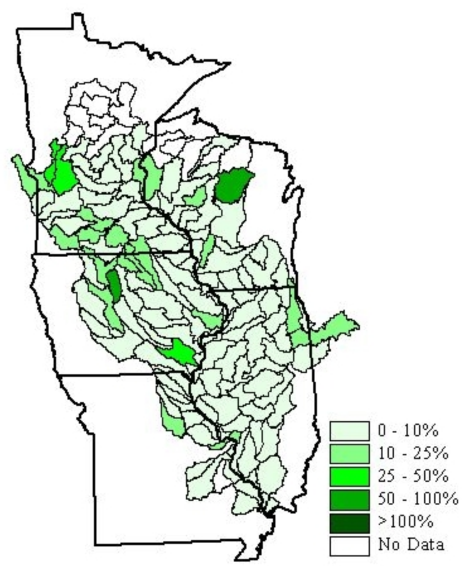


Figure 4. Ton-year carbon vs PDV of carbon accounting methods

A. Difference in location of land enrolled



B. Difference in carbon sequestered



[9]In all maps, 'No Data' indicates that no area is chosen in the sub-watershed.

Figure 5. Ton-year carbon vs sum of carbon accounting methods

A. Difference in location of land enrolled B. Difference in carbon sequestered