Carbon Sequestration in Agriculture: Value and Implementation

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Abstract

We investigate the value of carbon sequestration in a dynamic model, demonstrating that it is only a fraction of the value of emission abatement unless the sequestration is permanent. The magnitude of the fraction increases in the duration of sequestration, the natural decay rate of carbon and the discount rate. We also show that to optimally reduce the carbon stock, sinks should be utilized as early as possible. Further, we propose and assess three mechanisms to efficiently introduce sequestration into a carbon permit trading market, a pay-as-you-go system, a variable-length-contract system and a carbon annuity account system. We show that, although the three mechanisms may not be equally feasible to implement, they are all efficient.

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1 Introduction

Under the Kyoto Protocol, industrialized countries have pledged to reduce their carbon emissions to below their 1990 emission levels over the period 2008-2012. To fulfil their commitment, some countries, including the U.S., have proposed the inclusion of three broad land management activities pursuant to Article 3.4 of the Protocol, including forest, cropland and grazing land management. These activities can reduce atmospheric carbon stock by sequestering, or removing, carbon from the atmosphere and storing it in soil or biomass. For land rich countries like the U.S., Canada and Russia, carbon sequestration by these activities could potentially account for a significant part of their emission reduction commitments. For example, estimates indicate that the total carbon sequestration potential of U.S. cropland through improved management is 75-208 MMTC/year (Lal *et al* 1998). Soil sinks, combined with forest sinks, could be used by the U.S. to meet half of its emission reduction commitment (USDOS, 2000). However, skepticism remains among environmental groups who argue that "While preventing the emission of carbon dioxide is permanent, sequestering carbon pollution is a cheap, short-term fix that fails to address a long-term problem" (WWF, 2000).

The concerns raised by environmentalists and others relate specifically to the fact that sinks may be short run in nature and consequently, do not provide the same benefits as permanent emission reductions. This non-permanence issue related to carbon sinks has been at the center of the debate on incorporating soil carbon sequestration into the Kyoto Protocol (Chomitz, 1998). Numerous studies have empirically investigated the costs of forestry or agricultural sinks (Sohngen and Sedjo (2000), McCarl and Schneider (2000), Antle et al (1999), Marland et al (1999), Plantinga et al (1999), Stavins (1999), McCarl (1998), Mitchell (1997), Parks and Hardie (1995), Dudek and LeBlanc (1990)), but there has been little discussion on how to make sequestration and abatement projects commensurable. Richards (1997) discussed the time value of carbon, arguing that carbon reductions at different times may have different values. He also argued that under certain conditions, temporary carbon storage may have value. Fearnside (1997) suggested a "ton-years" accounting method, which was recommended by Chomitz (1998) in a report to the Carbon Offset Unit of the World Bank. In this accounting method, physical carbon is discounted so that 1 metric ton (MT) of carbon reductions t years in the future counts as just $1 - e^{-rt}$ MT reduction today, where r is the discount rate.

In this paper, we formally investigate the value of sequestration in a dynamic model that includes both emission reductions and sequestration as sources of greenhouse gas reductions. The model specifically addresses the non-permanence issue of sinks and compares the value of sinks with permanent emission reductions. We draw several important policy implications with immediate relevance for the design of systems that allow sinks as a way of achieving greenhouse gas reductions. First, we formally demonstrate that the social value of temporary sequestration is only a fraction of the value of permanent abatement, and derive the explicit relationship between the two. Second, we argue that to optimally reduce the carbon stock, carbon sinks should be utilized as early as possible, if they are used at all.

After investigating the efficient time path of emission control and sequestration, we turn to the design of mechanisms that can efficiently implement sinks. We propose three systems: a pay-as-you-go (PAYG) system, a variable-length-contract (VLC) system, and a carbon annuity account (CAA) system. Each could be used in conjunction with a well functioning (emission reduction based) carbon permit trading system to efficiently include the sequestration of carbon. We show that each system can be efficient, but requires different conditions to be so. Further, the systems are likely to differ in the transaction costs associated with their implementation. Consequently, one or more may be desirable in practice and under different circumstances.

Throughout the paper, we use the term “abatement” to refer to reductions in carbon loadings and “sequestration” to mean the storage of carbon in soils or other sources. Thus, abatement by its nature is permanent. If a ton of carbon is not produced and emitted into the atmosphere today, it will not be present in the atmosphere at a later date. In contrast, a ton of carbon stored in a sink today may be only temporarily out of the atmosphere as it might be released in a future period.

The remainder of the paper is organized as follows. In the next section, we set up the general model. In section 3, we use the model to analyze the optimal rates of carbon emission and sequestration and the value of carbon sequestration. Graphical illustrations are given and numerical examples are applied to a quadratic damage function to explore the value of sequestration relative to emission abatement. In section 4, we propose three mechanisms to implement sequestration in a permit trading environment and discusses their efficiency and feasibility. Concluding remarks are given in section 5.

2 Model Setup

Consider the social planner’s problem of maximizing the benefit of emissions minus the cost of sequestration and the damage caused by global warming. Let $e(t)$ be the carbon emission at time t and $B(e(t))$ be the benefit of emissions with $B(0) = 0$, $B'(\cdot) > 0$, and $B''(\cdot) < 0$. Let $C(t)$ be the total carbon stock in the atmosphere, and $D(C(t))$ be the total damage caused by $C(t)$, with $D'(\cdot) > 0$,and $D''(\cdot) > 0$. We also assume that $C(t)$ decays at an exponential rate, $\delta \geq 0$.

Let $A(t)$ be the total acres of land that are enrolled in carbon sequestration programs, and $Q(A(t))$ be the cost of enrolling $A(t)$ with $Q'(\cdot) > 0$, $Q(0) = 0$ and $Q''(\cdot) > 0$. The cost of carbon sequestration can be interpreted in two ways. If sequestration requires changing agricultural production practices, the cost may be the agricultural profit foregone for doing so. For example, switching from conventional to conservation tillage may reduce a farmer's profit (Pautch, Kurkalova, Babcock and Kling, 2000, Antle and Mooney, 1999), and some amount of profit may also be lost if cropland is converted to forestland (Plantinga et al, 1999). In the case of improved management of an existing forest stand, the cost of carbon sequestration is the expenditure incurred to enhance management, e.g., fertilization(Hoen and Solberg 1994, and Boscolo et al 1997).

The the cost function $Q(\cdot)$ can be convex for a variety of reasons. Different land may incur different sequestration costs: some highly productive land is best kept in conventional tillage and some land can be converted to forest without much economic loss. Typically, land with low sequestration cost is converted first. As the acreage A increases, the cost $Q(A)$ will increase at a faster rate when land of high sequestration cost is converted.[1] Let $\bar{A}$ be the total land area. We assume that $\lim_{A \to \bar{A}} Q(A) = \infty$, implying that all land will never be converted.

Let $a(t)$ be the acres of land newly enrolled ($a(t) > 0$) or withdrawn ($a(t) < 0$) in period t. For simplicity, we assume that when land is newly enrolled, carbon is *immediately* removed from the atmosphere, up to its full capacity of α tons per acre. Likewise, all of the stored carbon is completely and *immediately* released if the land is converted back to its original use. To capture in a simple way the fact that there are costs of converting land, we place bounds on the amount of land that can be

[1] If a substantial amount of land is diverted from agricultural production, agricultural output prices may increase and the profit reduction $Q(A)$ would be even greater. Then $Q(A)$ is likely to be convex even with homogeneous land.

converted each period: $\underline{a} \leq a(t) \leq \bar{a}$, with $\underline{a} < 0$ and $\bar{a} > 0$.

The equations of motion for $C(t)$ and $A(t)$ are

$$\dot{C}(t) = e(t) - \alpha a(t) - \delta C(t), \quad C(0) = C_0 > 0, \tag{1}$$

$$\dot{A}(t) = a(t), \quad A(0) = A_0 = 0, \quad 0 \leq A(t) \leq \bar{A}, \quad \underline{a} \leq a(t) \leq \bar{a}. \tag{2}$$

Equation (1) indicates that the change in the stock of carbon each period equals new emissions less the amount sequestered and the amount of natural decay. If r is the social discount rate, then the planner's net payoff function is

$$V^0(A, C, e, a) = \int_0^\infty \exp(-rt)[B(e(t)) - D(C(t)) - Q(A(t))]dt. \tag{3}$$

Maximizing (3) subject to (1) and (2) yields the optimal carbon sequestration and emission levels over time.

3 Optimal Path of Sequestration and Emissions

Since $\lim_{A \to \bar{A}} Q(A) = \infty$, the constraint $A(t) \leq \bar{A}$ is never binding along the optimal path. Then the current value Hamiltonian for the social planner's problem is

$$\begin{aligned} H(C, A, e, a, \lambda, \mu) &= B(e(t)) - D(C(t)) - Q(A(t)) \\ &\quad + \lambda(t)(e(t) - \alpha a(t) - \delta C(t)) + \mu(t)a(t) + \gamma(t)A(t), \end{aligned}$$

where $\lambda(t)$ and $\mu(t)$ are the costate variables and $\gamma(t)$ is the shadow value of the constraint $A(t) \geq 0$. The necessary conditions are

$$\frac{\partial H}{\partial e} = \lambda(t) + B'(e(t)) = 0, \quad \text{or} \quad -\lambda(t) = B'(e(t)), \tag{4}$$

$$\max_a H \quad \text{or} \quad a(t) \begin{cases} = \bar{a} \\ = \underline{a} \\ \in [\underline{a}, \bar{a}] \end{cases} \quad \text{if} \quad -\alpha\lambda(t) + \mu(t) \quad \begin{cases} > 0, \\ < 0, \\ = 0, \end{cases} \tag{5}$$

$$\dot{\lambda}(t) = r\lambda(t) - \frac{\partial H}{\partial C} = (r+\delta)\lambda(t) + D'(C(t)), \tag{6}$$

$$\dot{\mu}(t) = r\mu(t) - \frac{\partial H}{\partial A} = r\mu(t) + Q'(A(t)) - \gamma(t), \tag{7}$$

$$A(t) \geq 0, \quad \gamma(t) \geq 0, \quad A(t)\gamma(t) = 0 \tag{8}$$

$$\lim_{t\to\infty} e^{-rt}\lambda(t) = 0, \qquad \lim_{t\to\infty} e^{-rt}\mu(t) = 0. \tag{9}$$

From (6), we know

$$\lambda(t) = -\int_t^\infty \exp\left[-(r+\delta)(s-t)\right] D'(C(s))ds. \tag{10}$$

Thus $-\lambda(t)$ measures the total discounted (to period t) future damages caused by one more unit of atmospheric carbon in period t. Notice the symmetric role played by the natural decay rate, δ, and the social discount rate, r. Equation (4) simply says that the marginal benefit of emitting one unit of carbon must equal its marginal cost. Similarly, $\mu(t)$ measures the discounted costs of maintaining one acre of land in sequestration, and (5) indicates that land should be converted at its maximum speed whenever the benefit of land conversion $-\alpha\lambda(t)$ is different from the cost $\mu(t)$. The most rapid approach in land conversion is a natural outcome of the linearity of the planner's problem (or the Hamiltonian) in $a(t)$; that is, both the carbon stock and the land stock in sequestration are linear in the conversion rate $a(t)$.

We assume that a steady state exists (thus the transversality conditions in (9) are naturally satisfied). Setting $\dot{C} = 0$, $\dot{A} = 0$, $\dot{\lambda} = 0$ and $\dot{\mu} = 0$, from the conditions in (6) - (7) and the two state equations (1) - (2), we obtain the following description of the steady state:

$$\begin{aligned} &(i) \quad e^* = \delta C^*, \quad (ii) \quad B'(e^*) = \frac{D'(C^*)}{r+\delta}, \quad (iii) \quad \lambda^* = -\frac{D'(C^*)}{r+\delta}, \\ &(iv) \quad \mu^* = \alpha\lambda^* = -\frac{Q'(A^*)}{r}, \quad (v) \quad a^* = 0. \end{aligned} \tag{11}$$

The steady state levels of emission and stock e^* and C^* are uniquely determined by (11-i) and (11-ii), and are *independent* of the sequestration activities. That is, once the equilibrium emission and stock levels are attained, there is no role for additional carbon sequestration activities. However, from (11-iii) - (11-iv), we know $\lambda^* < 0$ and $A^* > 0$ (and consequently $\gamma^* = 0$). Thus, a certain amount of carbon in fact should be sequestered in the biomass in the steady state. Then the positive stock A^* must be the result of using sequestration during the transition path toward the steady state. In summary,

Remark 1 *Although carbon sequestration cannot efficiently provide a long-run solution to global warming on its own, it does enter the transition path, indicating a clear role for carbon sequestration in achieving the steady state. Thus, although emission reductions must ultimately be employed to maintain the efficient carbon stock, so too, sequestration should be employed "in the process," resulting in a permanent level of sequestered carbon.*

To analyze the transition path towards the steady state, we consider the phase diagram in the space of $e(t)$ and $C(t)$, shown in Figures 1 and 2. The equation of motion for $C(t)$ is given in (1). Setting $\dot{C} = 0$, we get

$$e(t) = \alpha a(t) + \delta C(t). \tag{12}$$

Thus the $\dot{C} = 0$ locus is linear and upward slopping, and its location depends on the value of $a(t)$. To derive the equation of motion for $e(t)$, we differentiate both sides of

(4), and get

$$\dot{\lambda}(t) = -B''(e(t))\dot{e}(t). \tag{13}$$

Plugging (4) and (13) into (6) and rearranging, we get

$$\dot{e}(t) = \frac{r+\delta}{-B''(e(t))}\left[\frac{D'(C(t))}{r+\delta} - B'(e(t))\right]. \tag{14}$$

Setting $\dot{e}(t) = 0$ leads to

$$\frac{D'(C(t))}{r+\delta} = B'(e(t)). \tag{15}$$

Finally, totally differentiating equation (15), we obtain

$$\frac{de}{dC} = \frac{D''(C(t))}{(r+\delta)B''(e(t))} < 0. \tag{16}$$

Thus the $\dot{e} = 0$ locus is downward slopping and is independent of the level of $a(t)$.

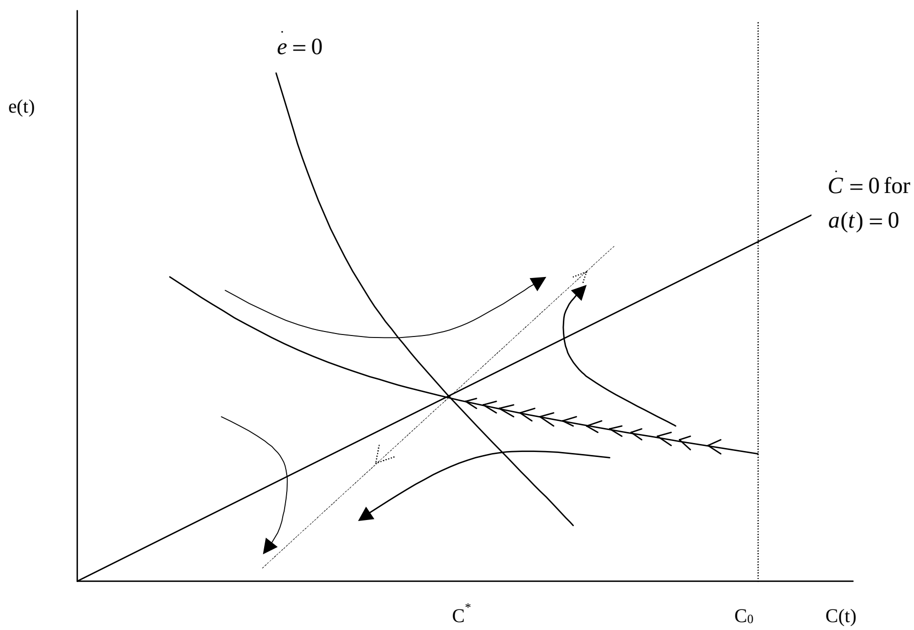


Figure 1: Phase Diagram for Carbon Emission and Stock (When a(t)=0)

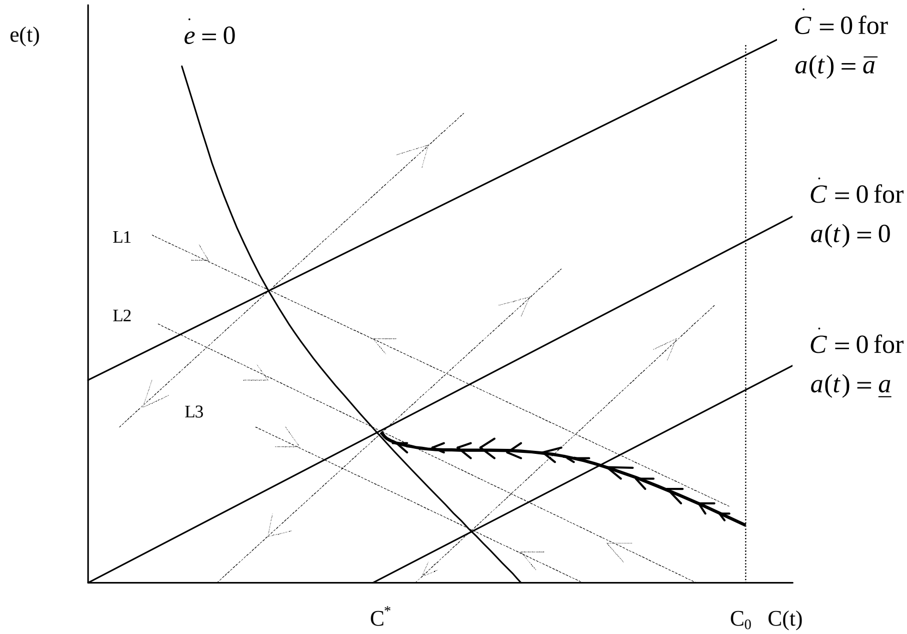


Figure 2: Phase Diagram for Carbon Emission and Stock (When a(t) Varies)

For each fixed level of $a(t) \in [\underline{a}, \bar{a}]$, there is a unique steady state and a saddle path passing through the steady state. Figure 1 presents the case of $a(t) = 0$ for all $t \geq 0$. We can show that the saddle paths for different levels of a do not cross. Of course, $a(t)$ is likely to change as the system evolves, and we need to characterize the path of $a(t)$ to find the optimal transition path.

We assume that the starting carbon stock level is to the right of the $\dot{e} = 0$ locus: the current carbon stock is higher than that in the steady state, so that the social planner's problem is to reduce this level over the long run. The assumption implies that $\dot{e}(t) > 0$: the emission level should always increase on the transition path. If the current emission level is high,[2] and if this level can be changed without adjustment costs, carbon emissions should be drastically reduced to be on the optimal transition

[2] The UNFCC(1999) states that the current atmospheric carbon stock is too high and that the carbon emission level is higher than what nature can assimilate.

path, and then be allowed to gradually increase.

In a model that explicitly considers adjustment costs of changing the emission levels, the initial reduction in emission should be slower, and intuitively sequestration could help ameliorate the emission adjustment needed. In fact, even without adjustment costs, sequestration raises the initial emission level on the optimal path. Since sequestration offers another way of reducing the carbon stock, the marginal social cost of the stock, $-\lambda(0)$, will likely be lower with the option of sequestration: at the worst, the social planner simply does not utilize sequestration, in which case $-\lambda(0)$ is not changed. But $-\lambda(0)$ strictly decreases if sequestration is utilized.[3] However, from (4), we know $e(t)$ is increasing in $\lambda(t)$, which implies that $e(0)$ increases under sequestration. That is, sequestration reduces the initially needed emission reduction. Further, as sequestration becomes more effective (i.e. higher α) or less costly (i.e. lower $Q(\cdot)$), the marginal damage of the initial carbon stock further decreases, raising $e(0)$. In summary,

Remark 2 *The optimal initial emission level,* $e(0)$, *is increasing in the effectiveness,* α, *and decreasing in the cost,* $Q(\cdot)$, *of sequestration. If moving to the saddle path would involve substantial cuts in current carbon emissions, sequestration will reduce the emission cut that is needed.*

The essence of Remark 2 is that sequestration serves as a (temporary) substitute for abatement in reducing the carbon stock. Since the paths of $e(t)$ and $C(t)$ are continuous,[4] $e(0) > 0$ implies that $e(t) > 0$ for certain initial periods of time. In

[3] This statement does not apply to later periods with $A(t) > 0$. After a certain amount of carbon has been sequestered, the sequestration "option" may in fact become a burden in that there is a cost of maintaining $A(t)$, thus it may become efficient to release carbon from the land. Then the marginal damage of the stock $-\lambda(t)$ may increase with the "sequestration burden."

[4] $C(t)$ is continuous by definition in (1). The continuity of $e(t)$ arises from the "emission smoothing" argument: since $B(e)$ is continuous and concave, smoothing out any jumps in e increases the

fact, we can conjecture that under reasonable conditions, $a(t) = \bar{a}$ during this initial period. If $C(0)$ is high and $A(0) = 0$, the marginal damage of carbon is high and the marginal cost of sequestration is low: $-\alpha\lambda(t) > -\mu(t)$. Then land should be converted into the sequestration program at its maximum speed.

The incentive to sequester carbon falls as the carbon stock decreases and the land stock increases. An interesting question is whether the social planner should use sequestration so much in early periods that eventually some land will need to be taken out of sequestration. In fact, this is true. As the system approaches the steady state, the optimal sequestration activity must involve taking land out of sequestration (although not at the maximum speed $\underline{a}$).

Proposition 1 *There exists a time $T < \infty$ such that $\underline{a} < a(t) < 0$ for all $t > T$.*

The proof is given in Appendix A. Intuitively, the steady state being "steady" implies that no radical land conversion should be undertaken as the system approaches it. Since the emission level is increasing as time goes by, it must be that the marginal damage of the stock $-\lambda(t)$ has been decreasing. But since $a(t)$ is strictly between $\underline{a}$ and $\bar{a}$, (5) implies that the marginal cost of maintaining land in sequestration $-\mu(t)$ must also be decreasing. Since the cost $Q(\cdot)$ is convex, we know the land area in sequestration $A(t)$ has to be decreasing, or land is being taken out of the sequestration program.

Figure 2 presents a sample transition path where initially $a(t) = \bar{a}$. The conversion rate $a(t)$ gradually decreases as time goes by, until at some moment $a(t) = 0$. Past this point, land is removed from sequestration ($a(t) < 0$) until the system approaches the steady state. In the end, some land remains sequestered forever.

Any optimal transition path is likely to involve this pattern of "sequester first and release later." We show in Appendix B that if the carbon stock can be reduced

cumulative discounted benefit. This can also be seen in (4) and the fact that $\lambda(t)$ is continuous.

only by sequestration (i.e. fixing e at a constant level zero and setting the natural decay rate δ to zero), the optimal land conversion pattern is $a(t) = \bar{a}$ until the steady state is reached (at finite time). That is, *if sequestration is ever used, it should be undertaken early.* The result is intuitive: since initially the carbon stock $C(0)$ is high and land stock $A(0)$ is low, the marginal benefit of sequestration (or the avoided marginal damage of the carbon stock) overcomes the marginal cost, and land should be converted at its maximum rate. Introducing emission or abatement $e(t)$ and natural decay into this system is likely to "smooth" out the conversion rate. Further, the fact that emissions actually increase overtime means that as a substitute, sequestration is even more valuable in early periods. Thus more land is to be converted into the program and eventually some land needs to be taken out, resulting in the "sequester first and release later" pattern.

This observation is relevant for the current debate on whether and *when* soil-based carbon sequestration should be used to satisfy the emission reduction targets under the Kyoto Protocol. The EU environment ministers recommended at a Council meeting in Luxembourg that "additional human-induced activities" related to changes in greenhouse gas emissions in agricultural soils, land-use change and forestry should not be included *until after the first commitment period of 2008-2012* (Weathervane, RFF, 2000). Our result argues to the contrary: if we are going to make use of sequestration at all, then we should start using it now.

4 The Value of Carbon Sequestration

Although phase diagrams are helpful in identifying the qualitative effects of carbon sequestration, they do not tell us how large the effects are. In this section, we derive formula for the value of (temporary) carbon sequestration and use numerical examples to demonstrate the value of carbon sequestration relative to emission reductions.

Let $\eta(t,\tau)$ be the value of storing one unit of carbon for τ periods starting from t. It measures the avoided damage for the period when this unit is stored. From (10), we can express $\eta(t,\tau)$ as

$$\eta(t,\tau) = \int_t^{t+\tau} \exp\left[-(r+\delta)(s-t)\right] D'(C(s))ds = -\lambda(t) + \exp(-r\tau)\lambda(t+\tau). \quad (17)$$

We know $\lambda(t)$ measures the discounted (to time point t) future damage caused by one unit of carbon stock in period t. If one additional unit of carbon is removed at t, then its contribution is $-\lambda(t)$. However, $\lambda(t+\tau)$ damage will be incurred if this unit of carbon is released at $t+\tau$. Equation (17) says that the value of storing one additional ton of carbon for τ periods is the difference between these two values.

Equation (17) indicates that $\eta(t,\tau)$ is decreasing in the discount rate r and the decay rate δ, given the carbon path $C(s)$ on $[t, t+\tau]$. Discounting reduces the present value of the damage from carbon, and also the damage avoided due to sequestration. For pollutants with a high decay rate, storing the pollutant also reduces the pollution that would have naturally dissipated, thereby reducing the value of temporary storage.

From (17), it is obvious that $\eta(t,\tau)$ increases in τ: the longer the unit of carbon is kept out of the atmosphere, the higher its value. Although less obvious, $\eta(t,\tau)$, in particular its present value, $e^{-rt}\eta(t,\tau)$, may decrease with t if the carbon stock is decreasing overtime and if the decay rate is low. The reason is that as the marginal damage decreases overtime, the contribution of each additional unit of carbon reduction becomes smaller. However, if the decay rate is high, postponing sequestration may be desirable since a higher stock in early periods also means more carbon is naturally dissipated for longer periods of time.

More strictly, note that $\frac{d\left[e^{-rt}\eta(t,\tau)\right]}{dt} = e^{-rt}(\dot{\eta} - r\eta)$. From (17) and (6), we know

$$\dot{\eta} - r\eta = \delta\eta + e^{-rt}D'(C(t+\tau)) - D'(C(t)). \quad (18)$$

Thus if $\dot{C}(t) < 0$ on $[t, t+\tau]$ and if δ is sufficiently low, the convexity of $D(\cdot)$ implies that the present value of $\eta(t,\tau)$ decreases in t. The value of sequestration is higher the earlier it is implemented. This result is particularly relevant for carbon which has a rather low natural decay rate[5]. If, however, the carbon stock is increasing overtime, in particular if the marginal damage of the carbon stock is increasing at least at the rate of interest, then the present value of sequestration will increase overtime. In this case, it may be reasonable to start utilizing sequestration at a later time. But as we showed in the last section, the carbon stock should decrease overtime along the optimal transition path, and sequestration should be utilized as early as possible. In summary, we know

Remark 3 *The present value of sequestration $e^{-rt}\eta(t,\tau)$ (i) decreases in the discount rate r and the decay rate δ given a carbon path; (ii) increases in the duration of sequestration τ; and (iii) decreases in the starting time t if the decay rate δ is low and the carbon stock is decreasing overtime.*

Figure 3 presents much of the intuition for these results. The dashed line represents a sample path of the carbon stock, with C^* being the steady state level. Suppose at time t_1, one unit of carbon is sequestered until t_2. The smaller carbon stock at t_1 leads to a lower level of carbon reduction due to the natural decay. Since sequestered carbon does not decay, the carbon released at time t_2 causes the stock to be above the original level without sequestration. With proper discounting, the value of sequestration is the difference between the damages of the areas A and C.

As the decay rate increases, area C becomes bigger relative to area A. In the extreme, for a pure flow pollutant, the only difference between areas A and C will be due to discounting. On the other hand, area C disappears for a pure stock pollutant.

[5] According to Nordhaus (1991), the value of δ is about .005.

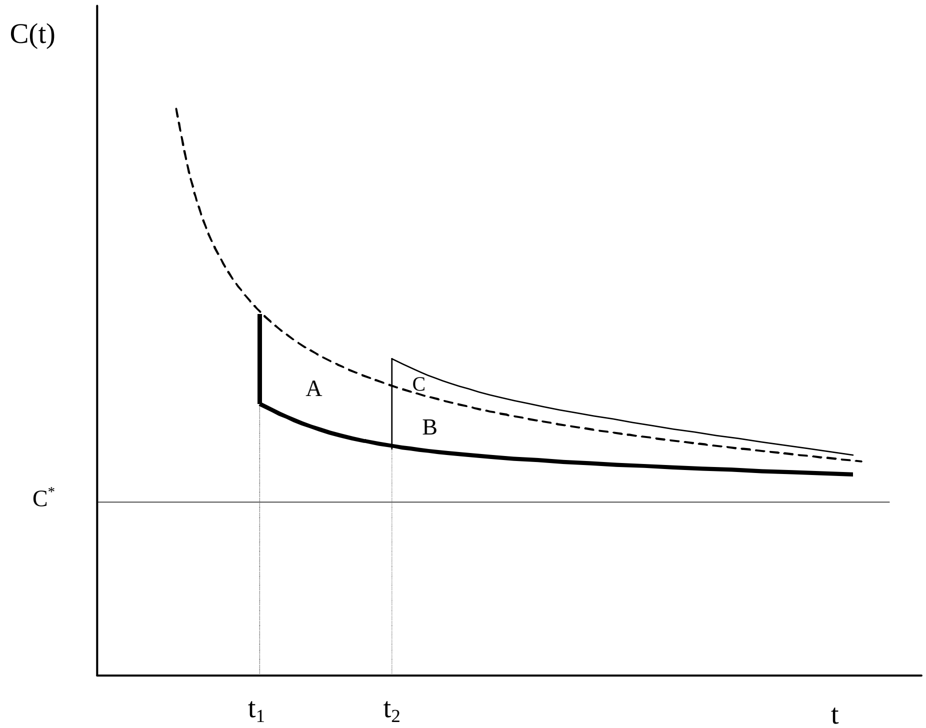


Figure 3: The Path of Carbon Stock With or Without Sequestration

Next we consider the value of sequestration relative to the value of (permanent) emission abatement, measured by the ratio

$$\tilde{\eta}(t,\tau) \equiv \frac{\eta(t,\tau)}{-\lambda(t)} = 1 - \exp(-r\tau)\frac{\lambda(t+\tau)}{\lambda(t)}. \tag{19}$$

Here we are interested in exploring the situations under which sequestration is of high (or low) value relative to abatement; hence situations in which sequestration has a potentially large (or small) role to play in the efficient approach to reducing atmospheric carbon levels. In Figure 3, the value of one unit of emission reduction at time t_1 is given by the damage of the area $A + B$.

Since $\lambda(t)$ is independent of τ, we know $\tilde{\eta}(t,\tau)$ increases in the sequestration duration τ. But the effects of r, δ and t on $\tilde{\eta}(t,\tau)$ become more complicated. We start with a simple case with linear damage function $D(\cdot)$ of constant marginal damage β.

From (17) we know

$$\eta_{\text{linear}}(t,\tau) = \frac{\beta}{r+\delta}(1-\exp(-r\tau)), \quad (20)$$

$$\tilde{\eta}_{\text{linear}}(t,\tau) = 1-\exp(-r\tau). \quad (21)$$

Thus, in the case of linear damages, the relative value of sequestration increases in the discount rate, and is independent of the decay rate δ or the starting date t.[6]

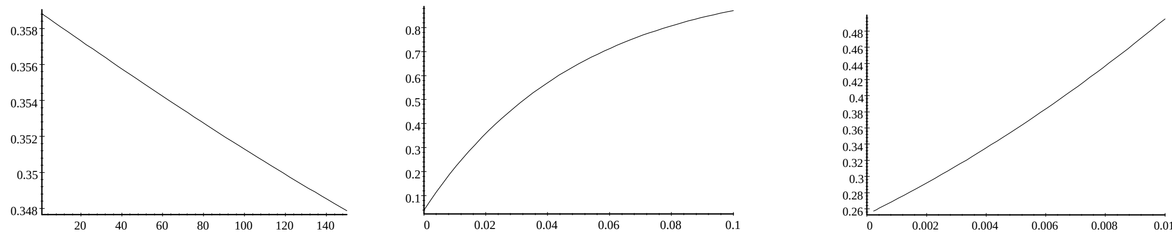
We use a numerical example, adapted from Falk and Mendelsohn (1993), to analyze the case with a more general damage function. The function is quadratic, with the marginal damage given by

$$D'(C(t)) = d_1 + 2d_2C(t). \quad (22)$$

We consider two scenarios in Falk and Mendelsohn (1993), a low MD scenario with $d_1 = -.0325$ and $d_2 = 4.06 * 10^{-14}$, and a high MD scenario with $d_1 = -.325$ and $d_2 = 4.06 * 10^{-13}$. We start with an initial carbon stock equal to 800 billion. We also assume two scenarios for the carbon stock path: increasing or decreasing over time. For the increasing case, we assume an annual emission level of 7.92 billion tons, which was the 1990 level. For the decreasing case, we arbitrarily use an annual emission level of 3.0 billion tons. Figures 4-5 show how the relative value of sequestration changes with respect to three parameters: the time when carbon storing starts, t, the discount rate r, and the dispersion rate δ[7]. When a plot is done with respect to one parameter, the other two parameters are held at their base levels, which are assumed to be: $r = .02$, $t = 0$, and $\delta = .005$.

[6] The result is consistent with the discussion of Chomitz (1998).

[7] Since the results for the high and low MD scenarios are almost identical, we only report results for the high MD scenario. Also, we use 150 years' carbon storage to approximate emission abatement. All plots are for carbon sequestration of 20 years.

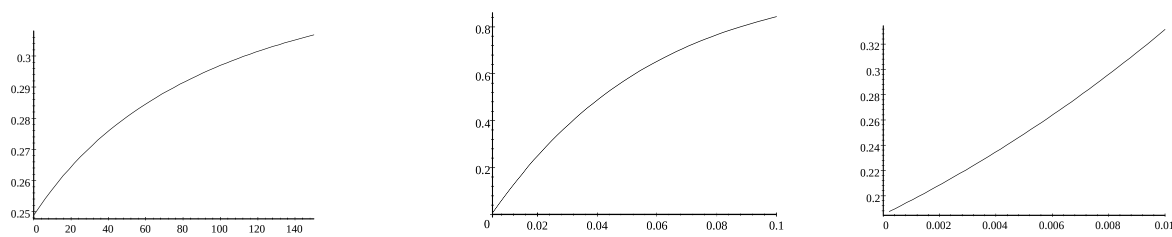


(a) Starting time: t

(b) Discount rate: r

(c) Decay rate: δ

Figure 4: Relative Values of Sequestration for a Decreasing Carbon Stock



(a) Starting time: t

(b) Discount rate: r

(c) Decay rate: δ

Figure 5: Relative Values of Sequestration for a Rising Carbon Stock

We first note from Figures 4b, 5b, 4c and 5c that the relative value of sequestration is increasing in r and δ. Intuitively, if we care less about the future, the fact that sequestered carbon has to be released again at a later date matters less, raising the value of sequestration relative to permanent reduction. From Figure 3, as the decay rate δ increases, the released carbon at t_2 will cause a smaller damage compared with permanent reduction, or area C will be smaller relative to area B due to the higher starting carbon stock at t_2 when sequestered carbon is released. Thus

$\tilde{eta}(t, \tau)$ increases in δ. Note also that the effects of r and δ on the relative value of sequestration are opposite to those on the (absolute) value $\eta(t, \tau)$.

For declining carbon stock, the relative value of sequestration is highest in the earliest periods as seen in Figure 4a. For an increasing carbon stock, the opposite is true (Figure 5a). The difference occurs because when the carbon stock declines, the damage becomes less severe as time goes on, thus earlier reductions are more valuable. But for an increasing carbon level, the converse is true. As shown in the diagrams, the value of storing one ton of carbon for 20 years is about 1/3 of the value of carbon abatement.

5 Mechanisms to implement Optimal Sequestration Levels

The models of the previous section indicate that sequestration can contribute to reductions of the atmospheric carbon stock. However, the value of sequestration is lower than that of emission abatement, unless sequestration keeps carbon out of the atmosphere permanently. Therefore, mechanisms to encourage the efficient amount of sequestration must appropriately reward permanent vs. temporary storage of carbon.

In this section, we propose and assess three distinct trading mechanisms, each of which can implement the socially optimal decision about carbon sequestration. We refer to the three mechanisms as Pay-As-You-Go (PAYG), Variable Length Contract (VLC), and Carbon Annuity Account (CAA). All three mechanisms are designed to be implemented within a well functioning permit market for carbon emission reductions. Thus, we assume there is a carbon permit trading system, and that the permit price in the system is efficient: $P(t) = B'(e(t)) = -\lambda(t)$. We analyze how trade between sources and sinks can take place efficiently, yielding the optimal amount of sequestration. We also discuss some of the potential advantages and drawbacks of the three mechanisms in terms of ease of implementation. Throughout this discussion, we will use the term "carbon credit" to mean a unit of carbon that is permanently removed from the atmosphere.

5.1 The Pay-As-You-Go (PAYG) System

In a PAYG system, owners of sinks sell (and repurchase) emission credits based simply on the permanent reduction of carbon. For example, in the first year, a farmer who adopts conservation tillage practices on 100 acres may earn 200 permanent carbon reduction credits which he can then sell at the going rate. If, in the fifth year, the farmer plows the field and releases all of his stored carbon, he would be required to purchase carbon credits from the market at the going price to cover his emissions.

In a world of certainty, the price trajectory $P(t)$ is known. Suppose there is perfect competition in the sink credit market. Then the competitive solution is equivalent to the problem of maximizing the present discounted revenue from carbon sequestration, $\alpha a(t)P(t)$, minus the sequestration cost $Q(A(t))$. Mathematically, the problem can be written as,

$$\underset{a(t)}{Max} \int_0^\infty [P(t)\alpha a(t) - Q(A(t))] \exp(-rt)dt \tag{23}$$
$$\text{s.t.} \quad \dot{A}(t) = a(t), \quad 0 \leq A(t) \leq \bar{A}, \quad \underline{a} \leq a(t) \leq \bar{a}.$$

The Hamiltonian is $H^1 = P(t)\alpha a(t) - Q(A(t)) + \mu(t)a(t) + \gamma(t)A(t)$, and the first order necessary conditions are

$$\max_a H^1 \quad \text{or} \quad a(t) \begin{cases} = \bar{a} \\ = \underline{a} \\ \in [\underline{a}, \bar{a}] \end{cases} \quad \text{if} \quad \alpha P(t) + \mu(t) \quad \begin{cases} > 0, \\ < 0, \\ = 0, \end{cases} \tag{24}$$

$$\dot{\mu}(t) = r\mu(t) - \frac{\partial H^1}{\partial A} = r\mu(t) + Q'(A(t)) - \gamma(t),$$

$$A(t) \geq 0, \quad \gamma(t) \geq 0, \quad A(t)\gamma(t) = 0$$

$$\lim_{t\to\infty} e^{-rt}\lambda(t) = 0, \qquad \lim_{t\to\infty} e^{-rt}\mu(t) = 0.$$

The first order conditions are exactly the same as (5) - (9). Together with the efficient permit price $P(t) = -\lambda(t)$, these conditions exactly replicate the social planner's choice of sequestration together with abatement. Therefore, given that the permit price equals the present discounted value of marginal damage, the PAYG is efficient. Given the obvious practical difficulties of implementing and enforcing such a system, we present the efficiency results in large part as a basis of comparison for the following two systems.

5.2 The Variable Length Contract (VLC) System

The VLC system would be likely to evolve through independent broker arrangements. If a broker wishes to buy permits from sink sources and sell them to emitters, the broker must contract with sink sources to achieve a permanent reduction in carbon. This could be accomplished by making a contract with one farmer to adopt conservation tillage for, say 3 years before plowing the field, contracting with a second farmer to plant trees beginning in year 4 for a certain number of years and so on. In each period, the broker might offer farmers a menu of prices associated with different contract lengths. In this system, private brokers provide the service of generating "permanent" carbon reductions from a series of separate temporary reductions.

Formally, suppose that a broker offers farmers a menu of prices for different contract lengths in each period. Let $q(t,\tau)$ be the price offered at time t for a contract with length τ. Then given this price menu, a farmer's decision is to maximize the net gain from carbon sequestration by choosing acres for contracts of different lengths. Let $a(t,\tau)$ be the acre of land enrolled at time t for a contract length of τ periods. The farmer's problem is

$$\begin{aligned} &\underset{a(t,\tau)}{Max} \int_0^\infty \exp(-rt) \left[\int_0^\infty q(t,\tau)\alpha a(t,\tau) d\tau - Q(A(t)) \right] dt \qquad (25) \\ \text{s.t.} \quad &\dot{A}(t) = \int_0^\infty a(t,\tau)d\tau - \int_0^t a(t-\tau,\tau)d\tau, \quad 0 \le A(t) \le \bar{A}, \\ &\underline{a} \le \dot{A}(t) \le \bar{a}, \end{aligned}$$

where $\int_0^\infty [q(t,\tau)\alpha a(t,\tau)]\, d\tau$ is the sum of total revenue at time t from contracts of all lengths; $\int_0^\infty a(t,\tau)d\tau$ is the total acreage at time t of newly enrolled land under contracts of all lengths, and, $\int_0^t a(t-\tau,\tau)d\tau$ is the total acreage of contracts expiring at time t.

Proposition 2 *The VLC system is efficient if*

$$q(t,\tau) = P(t) - \exp(-r\tau)P(t+\tau). \qquad (26)$$

For proof, see Appendix C. Notice the similarity between (17) and (26). If $P(t) = -\lambda(t)$, then $q(t,\tau) = \eta(t,\tau)$, which says that the price of carbon stored from time t to $t+\tau$ equals the marginal damage it reduces during this period. Proposition 2 says that if the price for sequestered carbon equals the damage it reduces, then VLC is efficient.

The condition in (26) will always be satisfied if there is no arbitrage in the trading of VLCs and emission permits. To see this, suppose a certain contract, say $\tilde{q}(t,\tau)$, is offered that is different from (26), and without loss of generality, suppose $\tilde{q}(t,\tau) > q(t,\tau)$. Then a broker can earn strictly positive profits by buying at time t an emission permit at $P(t)$, selling at t a VLC for the length of τ at $\tilde{q}(t, \tau)$, and selling at $t + \tau$ the emission permit at $P(t + \tau)$. The strategy clearly covers the broker's position: at each moment, the broker's balance of net emission is zero. However, the broker's loss in buying and selling the emission permit, $-P(t) + e^{-r\tau} P(t + \tau) = -q(t, \tau)$, is more than covered by the gain in selling the VLC, $\tilde{q}(t, \tau)$, leading to the arbitrage opportunity.

Arbitrage opportunities are not likely to arise if the emission permit and VLC trading is perfectly competitive. For a global pollutant like carbon with countless emission sources, the emission permit market is likely to be competitive. The nature of the VLC market will depend on the geographical distribution of the sinks and the brokers. It can be competitive if multiple brokers operate in each geographical area of carbon sinks. Since the owners of the sinks (i.e. farmers) do not have to directly "pay out" when carbon is released, the VLC approach is likely to be more feasible to implement compared with the PAYG system.

The "ton-years" accounting method mentioned in the introduction section can be made equivalent to the VLC if the correct discount factor is used. According to the "ton-years" accounting method, the amount of carbon sequestered is directly discounted, while in the VLC system, the price of sequestration is discounted. In both methods, the "correct "discount factor (either for quantity or price), depends on the duration of sequestration, the discount rate for future damage and the natural decay rate of carbon. However, directly discounting carbon works only for the case of linear damage function, as shown in (21).

5.3 The Carbon Annuity Account (CAA) System

Finally, a CAA system may be the most straightforward to implement of all three systems. In this system, the generator of a sink is paid the full value of the permanent reduction in the GHG's stored in the sink, but the payment is put directly into an annuity account. As long as the sink remains in place, the owner can access the earnings of the annuity account, but not the principal. The principal is withdrawn (or confiscated) when and if the sink is removed (e.g. the soil is tilled or other change is made to release the stored carbon). If the sink remains permanently, the sink owner eventually earns all of the interest payments, the discounted present value of which equals the principal itself - the permanent permit price. We now show that a CAA system is efficient.

Let $M(t)$ be the balance in the CAA account. Then in each period, $M(t)r$ will be the farmer's revenue, and $Q(A(t))$ will be her cost. The farmer's objective is to maximize the present discounted value of net revenue.

$$\underset{a(t)}{Max} \int_0^{\infty} [M(t)r - Q(A(t))] \exp(-rt)dt \tag{27}$$
$$\text{s.t.} \quad \dot{A}(t) = a(t), \quad 0 \leq A(t) \leq \bar{A}, \quad \underline{a} \leq a(t) \leq \bar{a},$$
$$\dot{M}(t) = \alpha a(t) P(t).$$

Let $\theta(t)$ be the costate variable for $M(t)$. Then the current value Hamiltonian is $H^2 = M(t)r - Q(A(t)) + \theta(t)\alpha a(t)P(t) + \mu(t)a(t) + \gamma(t)A(t)$, and the necessary conditions are,

$$\max_a H^2 \quad \text{or} \quad a(t) \begin{cases} = \bar{a} \\ = \underline{a} \\ \in [\underline{a}, \bar{a}] \end{cases} \quad \text{if} \quad \theta(t)\alpha P(t) + \mu(t) \begin{cases} > 0, \\ < 0, \\ = 0, \end{cases} \tag{28}$$

$$\dot{\theta}(t) = r\theta(t) - \frac{\partial H^2}{\partial M} = r\theta(t) - r = r(\theta(t) - 1), \tag{29}$$
$$\dot{\mu}(t) = r\mu(t) - \frac{\partial H^2}{\partial A} = r\mu(t) + Q'(A(t)) + \gamma(t).$$

Rearranging (29), we know $\frac{d}{dt}(\theta(t) - 1) = r(\theta(t) - 1)$, which implies that $\theta(t) - 1 = \exp(rt)(\theta(0) - 1)$. But since $\theta(0) = 1$, that is, the marginal value of money in period zero is equal to one, we known $\theta(t) = 1$ for all t. Then the necessary conditions are the same as those in the PAYG system. Thus the CAA system is efficient.

6 Discussion and Final Remarks

Resolving the permanence issue will be key to introducing carbon sequestration into the Kyoto Protocol or any other international agreement concerned with global warming. In this paper, we have addressed this issue directly with a simple model of carbon emission and sequestration dynamics. Several valuable policy insights come directly from the framework. First, the view that carbon sequestration should not be used to address global warming is not warranted from a theoretical perspective. As demonstrated, carbon sequestration can and should be used as a short run strategy to reduce the global atmospheric carbon stock. Ultimately, as long as there is less carbon in the air, it does not matter whether the reduction is done by sequestration or emission abatement.

The insights concerning the efficient and early use of sequestration shown in this paper are particularly interesting in light of the current policy forum about global warming. Some businesses and even some nations, including the U.S., are very reluctant to take actions to reduce carbon emissions. Sequestration can reduce the pressure on emission abatement in current periods, providing time to develop political support for and the technological capability to reduce carbon emissions.

However, despite the clear theoretical role for carbon sequestration, it is equally clear that it should not be treated the same as carbon emission reductions. Sequestration, by its nature, always has the potential to be temporary; consequently, it cannot be attributed the same value that emission reductions have if an efficient solution is to be obtained. The correct view is that sequestration has value, but the value is different from (and less than) the value of direct emission reduction. Therefore, special mechanisms should be used to address the difference. We define three such systems and demonstrate the efficiency properties of each of them.

To properly implement any of the three systems, we will need accurate approaches to measure the amount of carbon stored in agricultural sinks. Likewise, for carbon trading to occur between sinks and emission sources, all three systems need price information from outside the agricultural sector. PAYG and CAA both require the current permit prices and VLC requires prices of temporary carbon storage for all lengths of duration. Note that there is nothing preventing the simultaneous use of all systems.

Given that all three systems can be demonstrated to yield the theoretically efficient solution, the choice between which, if any, of these systems to actually implement may largely depend on the costs involved of implementation as well as the general acceptability of the approach to all involved. On this score, we suspect that the repayment obligations inherent in the PAYG system will render it politically infeasible.

A Proof of Proposition 1

Proof. Exponential decay of the carbon stock implies that the steady state will be reached only in the infinite time. Then the finiteness of $\bar{A}$ means that $a(t)$ cannot be $\underline{a}$ or $\bar{a}$ after T. Suppose, without loss of generality, $a(t) = \underline{a}$ at some time t_1 after certain T. That is, $\mu(t_1) - \alpha\lambda(t_1) < -\epsilon_1 < 0$ for some $\epsilon_1 > 0$. If T is sufficiently big, we know there exists $\epsilon_2(T) > 0$ such that $|\alpha\dot{\lambda}(t)| < \epsilon_2$ and $|\dot{\mu}(t)| < \epsilon_2$ for $t > T$. Thus $|\alpha\dot{\lambda}(t) - \dot{\mu}(t)| < 2\epsilon_2$ for all $t > T$. Choose T such that $2\epsilon_2 < \epsilon_1/\bar{A}$. Then we know $\mu(t)$ will be lower than $\alpha\lambda(t)$ after t_1 for a sufficiently long period of time that the land converted back to the sequestration program will be higher than $\bar{A}$, violating the land availability constraint. Thus after certain time T, $a(t)$ cannot be $\underline{a}$ or $\bar{a}$ at any moment.

Therefore, for $t > T$, $-\alpha\lambda(t) + \mu(t) = 0$. This equation, combined with (6) and (7), implies that, for $\forall t > T$, $\dot{\lambda}(t) = r\lambda(t) + \frac{Q'(A(t))}{\alpha} - \frac{\gamma(t)}{\alpha}$. Since $\dot{e}(t) > 0$, from (4) we know $\dot{\lambda}(t) = -B''(e(t))\dot{e}(t) > 0$. Thus $r\lambda(t) > -\frac{Q'(A(t))}{\alpha} + \frac{\gamma(t)}{\alpha}$. At the steady state, $r\lambda^* = -\frac{Q'(A^*)}{\alpha}$. $\lambda(t) < \lambda^*$ then implies that $\frac{Q'(A(t))}{\alpha} > \frac{Q'(A)}{\alpha} - \frac{\gamma(t)}{\alpha} \geq \frac{Q'(A^*)}{\alpha}$. From the convexity of $Q(\cdot)$, we know $A(t) > A^*$, or $a(t) < 0$ for all $t > T$. ■

B A special case with only carbon sequestration

For this special case, we can show that the following Lemma is true.

Lemma 1 *If the system reaches steady state (or a steady state exists), then there cannot be a switch in land transformation, i.e.,* $a(t)$ *cannot go from* $\overline{a}$ *to* $\underline{a}$*, or from* $\underline{a}$ *to* $\overline{a}$.

Put it differently, Lemma 1 says if at $t = 0$, $a(0) = \overline{a}$, then $a(t) = \overline{a}$, $\forall\ t \in [0, T]$, where T is the moment the system reaches steady state. If $a(0) = \underline{a}$, then $a(t) = \underline{a}$, $\forall\ t \in [0, T]$. In the absence of carbon emission, Lemma 1 tells us how we should utilize carbon sequestration to reduce the damage of global warming effects. When carbon damage is very high, and sequestration cost is low, land should be enrolled for carbon sequestration at the fastest rate. It is never optimal to take enrolled land out of carbon sequestration program. On the other hand, if sequestration cost is high relative to carbon damage, land should be taken out of the sequestration program at the fastest rate and land taken out now should never be enrolled again. One implication of the latter case is that: If it is not optimal to enroll land for carbon sequestration now, then it will never be optimal to do so.

Proof. Without loss of generality, suppose the system starts with $a(0) = \overline{a}$. Suppose at t_1, the system takes a switch, i.e., $a(t) = \overline{a}, \forall t \in [0, t_1]$ and $a(t) = \underline{a}, \forall t \in [t_1, t_2]$,where $t_2 \leq T$. Note that $a(t) = \overline{a}, \forall t \in [0, t_1] \Longrightarrow \mu(t) \geq \alpha\lambda(t), \forall t \in [0, t_1]$; $a(t) = \underline{a}, \forall t \in [t_1, t_2] \Longrightarrow \mu(t) \leq \alpha\lambda(t), \forall t \in [t_1, t_2]$. This, combined with the continuity of $\mu(t)$ and $\lambda(t)$, implies $\dot{\mu} \leq \alpha\dot{\lambda}$ at t_1. However, $\mu = \alpha\lambda$ at t_1,(again due to the continuity of $\mu(t)$ and $\lambda(t)$). Then, because of (5) and (6), it must be that $Q'(A) \leq \alpha D'(C)$ at t_1. After t_1, $a(t) = \underline{a} \Longrightarrow A(t)$ decreases and $C(t)$ increases for $t \in (t_1, t_2)$. Thus, $Q'(A) < \alpha D'(C)$ $t \in (t_1, t_2) \Longrightarrow \dot{\mu} < \alpha\dot{\lambda}$ and $\mu(t) < \alpha\lambda(t)$ $\forall t \in [t_1, t_2]$. We know t_2 cannot be T, because at $T, \mu = \alpha\lambda$. But we have just shown that before $t_2, \mu(t)$ and $\alpha\lambda(t)$ are becoming further apart. Moreover, t_2 cannot be another switching point, otherwise, it would mean $\mu = \alpha\lambda$. Therefore, $t_2 = \infty$, which violates the existence of a steady state. ■

C Proof of Proposition 2

Proof. Define $\tilde{a}(t)$ as follows,

$$\tilde{a}(t) \equiv \dot{A}(t) = \int_0^\infty a(t, \tau)d\tau - \int_0^t a(t - \tau, \tau)d\tau. \qquad (C1)$$

We show below Problem (25) is just the same as Problem (23) with $\tilde{a}(t)$ in place of $a(t)$. We have shown the solution to Problem (23) is efficient. If both problems are the same, then the solution to Problem (25) also has to be efficient. Plug $(C1)$ into the objective function of problem (25), we get

$\int_0^\infty \exp(-rt)[\int_0^\infty [q(t, \tau)\alpha a(t, \tau)d\tau - Q(A(t))]dt$

$= \int_0^\infty \exp(-rt)[\int_0^\infty [(p(t) - \exp(-r\tau)p(t + \tau))\alpha a(t, \tau)d\tau - Q(A(t))]dt$

$= -\int_0^\infty \exp(-rt)Q(A(t))]dt + \int_0^\infty \exp(-rt)[\int_0^\infty (p(t)\alpha a(t, \tau)d\tau]dt$

$-\int_0^\infty \exp(-rt)[\int_0^\infty \exp(-r\tau)p(t + \tau))\alpha a(t, \tau)d\tau]dt$

$= -\int_0^\infty \exp(-rt)Q(A(t))]dt$

$+\int_0^\infty \exp(-rt)[\int_0^\infty (p(t)\alpha a(t,\tau)d\tau]dt - \int_0^\infty \exp(-rt)[\int_0^t p(t)\alpha a(t-\tau,\tau)d\tau]dt$

$= -\int_0^\infty \exp(-rt)Q(A(t))]dt + \int_0^\infty \exp(-rt)[\int_0^\infty (p(t)\alpha a(t,\tau)d\tau - \int_0^t p(t)\alpha a(t-\tau,\tau)d\tau]dt$

$= -\int_0^\infty \exp(-rt)Q(A(t))]dt + \int_0^\infty \exp(-rt)p(t)\tilde{a}(t)dt$

The third line follows because of the following,

$\int_0^\infty \exp(-rt)[\int_0^\infty \exp(-r\tau)p(t+\tau))\alpha a(t,\tau)d\tau]dt$

$= \int_0^\infty \int_0^\infty \exp(-r(r+\tau))p(t+\tau))\alpha a(t,\tau)dtd\tau$(By change of integration order)

$= \int_0^\infty \int_\tau^\infty \exp(-rx))p(x))\alpha a(x-\tau,\tau)dxd\tau$(By change of variable, $x = t+\tau, y = \tau$)

$= \int_0^\infty \int_0^x \exp(-rx))p(x))\alpha a(x-\tau,\tau)d\tau dx$(By change of integration order)

$= \int_0^\infty \exp(-rt)[\int_0^t p(t)\alpha a(t-\tau,\tau)d\tau]dt.$

■

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