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CO_2 Offset Options: Comparative Assessment of Terrestial Sinks vs. Natural Gas Combined Cycle [1]

Abstract

This study compares the economic value of two CO_2 mitigation actions: terrestrial reforestation to sequester CO_2 emitted from coal-fired power generation versus natural gas combined cycle (NGCC) power generation to avoid (minimize) CO_2 release. The same quantity of carbon offset was assumed for both actions. Tree stock growth, carbon absorption/release cycles, and replanting were considered to maintain the quantity of carbon offset via reforestation. The study identified important parameters with both CO_2 mitigation options that should be considered when examining alternative strategies.

Introduction

Concern over the possible consequences of potential global warming, induced by anthropogenic sources of carbon emissions, have led to a variety of proposed mitigation strategies. One option would utilize the natural process of carbon absorption by growing trees to "sequester" some quantity of excess carbon dioxide (CO_2) in the atmosphere.

To date, analyses of this strategy have focused on its short-run cost effectiveness; relatively little attention has addressed the long-run effects of a carbon sequestration strategy. For example, important issues arise with respect to assumptions regarding

- the time it takes for atmospheric CO_2 concentrations to adjust to a change in the quantity of emissions and the composition of sinks, and
- the disposition of the carbon stored in reforested areas as trees reach maturity.

This paper examines how varying these assumptions might affect the relative magnitudes of long-run effects associated with alternative carbon sequestration policies. In particular, the paper considers how assumptions about specific issues—the atmospheric half-life of additional CO_2 emissions, the duration of the proposed policy, and the nature of the CO_2 damage function—might influence the long-run effects and corresponding cost-effectiveness of carbon sequestration. It also considers the cost-effectiveness of an

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[1] This paper is based on an unpublished 1994 manuscript *An Economic Assessment of Sequestering Excess Atmospheric Carbon in Trees* by J.L. Carlson, D.W. South and D. Gabaldon, prepared with funding from the U.S. Department of Energy under Contract W-31-109-Eng-38.

alternative strategy to control excess carbon emissions, as well as the potential benefits of such a policy. The results raise serious questions about the potential cost-effectiveness of carbon sequestration, as well as the net benefits that could be realized.

Determinants of Long-Run Carbon Sequestration Effects

Analyses of the viability of carbon sequestration have tended to focus on the total amount of carbon that could be sequestered per unit of additional forestland and the cost-effectiveness of such strategies. Less attention has been devoted to the temporal dimensions of such policies and the resulting implications for costs and benefits over the long run.

Both the short-run and long-run effects of a carbon sequestration policy will be influenced by such factors as[2]

- the atmospheric half-life of excess CO_2,
- the duration of the sequestration policy,
- the time path of reforestation, and
- related issues—including the disposition of sequestered carbon as trees reach maturity, and the characteristics of the CO_2 damage function.

For a fixed emissions rate and stock of atmospheric CO_2, sequestration and the atmospheric lifetime of excess CO_2 combine to determine the atmospheric concentration of CO_2 at any future point in time. To the extent that the half-life of excess atmospheric CO_2 is longer or shorter, the effects of sequestering carbon for a limited amount of time will vary. If the atmospheric half-life of excess CO_2 is infinite, any short-run reduction in the stock of atmospheric CO_2 through sequestration would be beneficial.[3] This is so because the damages attributable to the sequestered carbon are avoided for the duration of the policy. Subsequent re-release of the sequestered carbon simply returns the atmospheric concentration to what it would have been in the absence of the sequestration policy.

In contrast, if excess atmospheric CO_2 has a 50-year half-life, the long-run effects of sequestration are uncertain. Three outcomes, illustrated in Figure 1 by the curves labeled S_{p1}, S_{p2}, and S_{p3}, are possible.[4] Assume first that when the sequestered carbon is re-released, it increases the atmospheric concentration of CO_2, but to a level that is less than what it would have been in the absence of the sequestration policy. This outcome is illustrated by the curve labeled S_{p1}. In this case, there is some long-run beneficial effect attributable to the policy. However, the net effect is not as large as it would be in the case where the atmospheric half-life is infinite.

In the second and third cases, illustrated by S_{p2} and S_{p3}, it is possible that the re-release of the sequestered carbon could increase the atmospheric concentration of CO_2 to an amount

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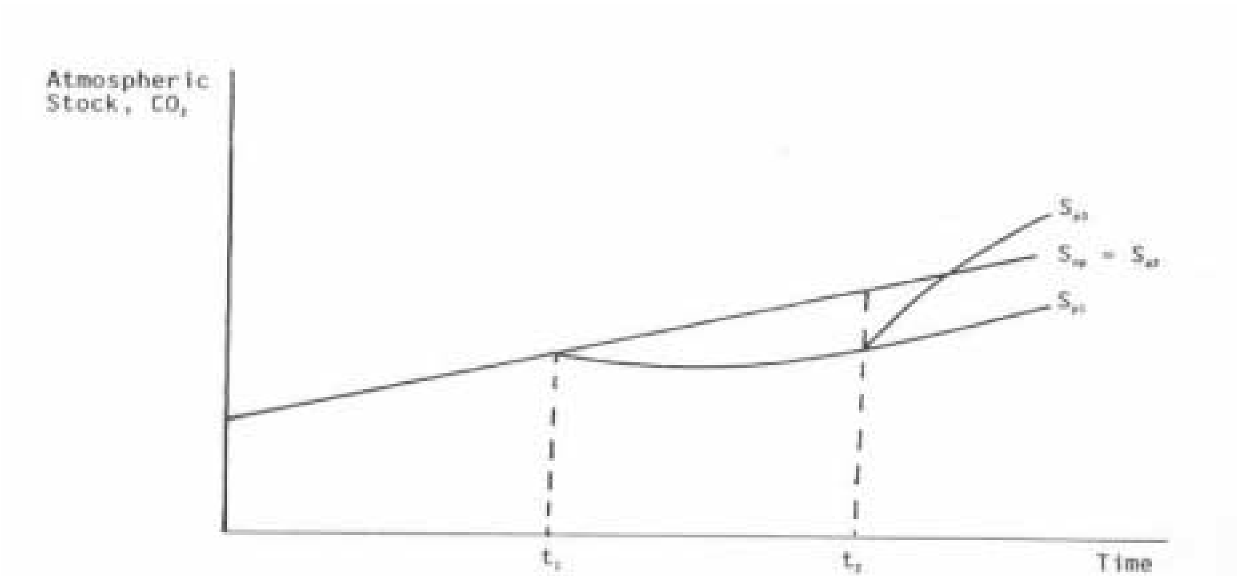
[2] More detailed discussion of each factor is contained in the referenced manuscript (footnote 1). Only atmospheric half-life is discussed here.

[3] This is not meant to imply, however, that *net* benefits necessarily would be positive.

[4] Note that S_{p1}, S_{p2}, and S_{p3} coincide up to point t_2.

equal to, or greater than, what it would have been in the absence of the policy. These possibilities exist because the quantity of carbon that is sequestered remains fixed for the duration of the time that it is stored in trees—i.e., it is unaffected by the assumption of the 50 year-half-life.

Figure 1 Effects of Sequestration and Re-Release on the Atmospheric Stock of CO_2: 50-Year Half-Life



Why? In the absence of sequestration, the carbon in question would slowly be cycling out of the atmosphere. However, once carbon is sequestered, the "cycling effect" ceases for that quantity sequestered. Thus, re-release could result in additional damages that exactly offset the beneficial effects of the initial sequestration. Moreover, the re-release of the sequestered carbon could result in additional damages that more than offset the short-run benefits of the policy. The magnitude of such long-run adverse effects would be determined by the

- actual time path of removal of excess atmospheric CO_2 to other sinks (e.g., deep ocean) and
- shape of the damage function, which relates the amount of damages from global warming to the stock of excess atmospheric CO_2.

Modeling Cost-Effectiveness of Carbon Sequestration

The potential effects of alternative assumptions about the atmospheric residence time of CO_2 and the re-release of sequestered carbon were considered by examining different scenarios. The effect of the half-life of atmospheric CO_2 was examined by considering two possibilities—a 50-year half-life versus an infinite half-life. Discount rates of 0%, 3% and 5% were used.

The effect that re-release of stored carbon could have on the costs of a particular policy was captured by considering three possibilities:

1. permanent storage of the sequestered carbon, i.e., 0% re-release;
2. 25% re-release of sequestered carbon as trees mature; and
3. 75% re-release of sequestered carbon as trees mature.

In the cases where partial re-release was assumed to occur, re-release was modeled by assuming that one fifth of the total amount would be released each year beginning in the 26th year of the policy scenario. Thus, for both the 25% and 75% re-release scenarios, sequestered carbon would be re-emitted to the atmosphere during years 26-30.

A number of simplifying assumptions were made concerning the average amount of carbon sequestered each year, the costs of implementing the proposed policy, the length of the growing cycle, and the disposition of mature trees in reforested areas. The sequestration rate was set at 70 million tons of carbon per year. This amount, which represents approximately 5 percent of 1990 U.S. carbon emissions, is consistent with an estimate of the amount of carbon emissions that could be eliminated through fuel switching (from coal to natural gas) without having to incur significant capital costs.

The costs incurred to sequester carbon were based on the analysis presented in Moulton and Richards.[5] In their analysis, Moulton and Richards did not specify a value for the length of the growing cycle—based on other analyses we assumed a 25-year cycle. It also was necessary to determine the required amount of forest resources necessary to achieve the assumed annual sequestration target. This required accounting for the fact that the amount of carbon sequestered by a tree varies over time, increasing initially, and then slowly leveling off and then falling to zero as the tree reaches maturity.

Thus, it was assumed that the amount of carbon sequestered each year would grow at a rate of 20% per year for the first five years of the growing cycle, remain constant for the next 15 years, and then decline to 0 over the remaining 5 years of the twenty-five year cycle. Using these assumptions it was then possible to determine the total amount of acreage that would have to be reforested in order to achieve the annual sequestration target of 70 million tons per year.

In those scenarios in which it was assumed that some positive amount of re-release would occur, the stock of reforested area was adjusted to ensure that the *net* average annual amount of carbon sequestered would equal the target amount, i.e., 70 million tons per year. This adjustment was factored into each growing cycle. To be specific, in each re-release scenario, the stock of reforested land was increased during each growing cycle to account for the amount of carbon that would be re-released at the end of the growing cycle. This

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[5] Moulton, R.J. and K.R. Richards, 1990, *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States*, U.S. Department of Agriculture, Forest Service, General Technical Report WO-58.

adjustment has the effect of increasing the costs of a carbon sequestration policy as the amount of carbon assumed to be re-released at the end of each growing cycle increases.

Cost-Effectiveness of Sequestration Policies

Cost-effectiveness values were calculated by dividing the present value of the costs of each policy scenario by the net amount of carbon sequestered over the 50 year time period (3.5 billion tons). In the case of fuel switching, 3.5 billion tons is the total amount of carbon emissions avoided as a result of the policy.

Based on the cost-effectiveness analysis summarized in Table 1, carbon sequestration would be more cost-effective than fuel switching, over the first 50 years, as a means of achieving a reduction in the stock of atmospheric CO_2. This result holds for the range of re-release rates and discount rates considered.

However, depending on how the sequestered carbon is managed over the longer run (> 50 years), this outcome could be reversed. To be specific, if at the end of the policy period some amount of the sequestered carbon is re-released, the cost-effectiveness of carbon sequestration would diminish. In the limit, as the amount of sequestered carbon that is re-released approaches 100 percent, the cost per ton of sequestered carbon would approach infinity.

Table 1 Cost-Effectiveness of Alternative Strategies to Reduce Atmospheric CO_2 (1994\$/ton CO_2; 70 million tons/year for 50 years)

	Discount Rate		
Carbon Policy	0 Percent	3 Percent	5 Percent
Carbon Sequestration			
0 percent re-release	$16.75	$8.86	$6.42
25 percent re-release	$17.98	$9.50	$6.88
75 percent re-release	$83.95	$43.91	$31.55
Fuel Switching	$343.01	$140.47	$85.93

The preceding discussion highlights a fundamental difference between the two policy strategies:

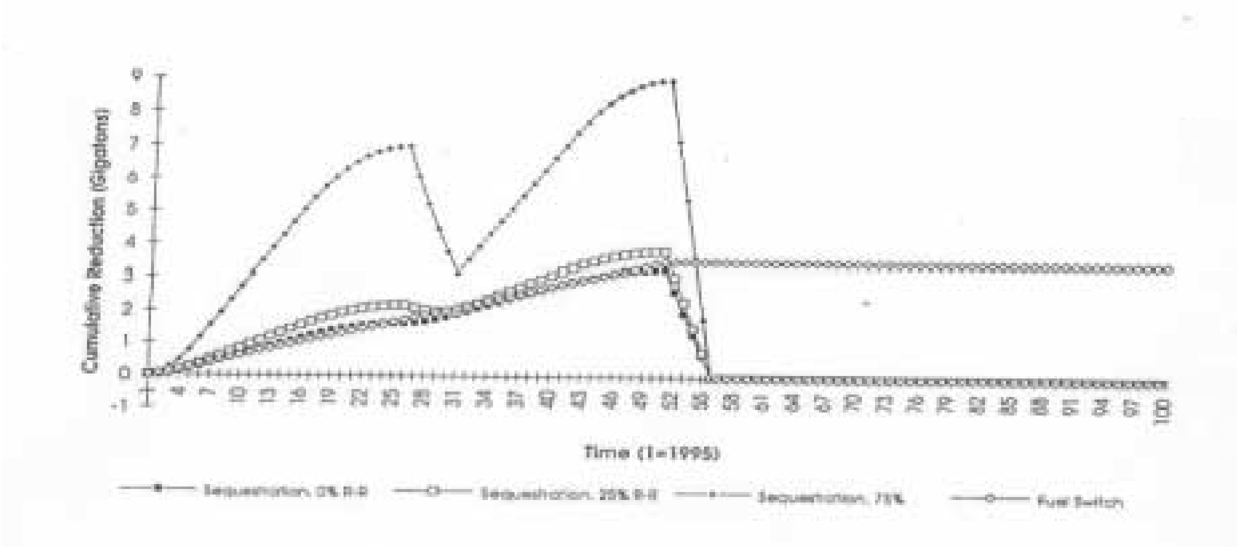
- Fuel switching results in a *permanent* reduction in both the amount of carbon that is emitted into the atmosphere over time, and therefore the stock of atmospheric CO_2 in the future (relative to the baseline).
- Sequestration merely results in the management of emissions after they occur. By itself, sequestration does nothing to alter the time path of emissions.

Moreover, over the long run, sequestration combined with re-release could cause the stock of atmospheric CO_2 to increase relative to the baseline. Depending on the ultimate fate of sequestered carbon and the damage function associated with global warming it is possible that, over the long run, sequestration could result in additional adverse effects.

Figures 2 and 3 depict the change in the atmospheric stock of CO_2 relative to the baselineover time for each policy scenario.[6] Figure 2 illustrates the effect of an assumed infinite half-life for excess atmospheric CO_2. Even in the case in which all of the carbon that is sequestered is eventually re-released, the policy would nonetheless yield positive benefits (although not necessarily positive *net* benefits) in the form of avoided damage costs. This follows from the fact that even with re-release, the atmospheric stock of CO_2 would be no greater than it would have been in the absence of any policy intervention. In this case, the benefits (avoided costs) would be measured by applying estimates of the value of a reduction in the stock of atmospheric CO_2 to the quantities indicated in Figure 2.

Figure 3 illustrates the change in atmospheric stock for the case of a 50-year half-life for excess atmospheric CO_2. Note that in the years following the end of each sequestration policy, the net change in the atmospheric stock of CO_2 is negative—i.e., the atmospheric stock of CO_2 exceeds the stock that would occur in the absence of policy intervention. As such, during this time period, damages attributable to excess CO_2 are larger than they would have otherwise been. Depending on the nature of the damage function for CO_2, the increased damages could outweigh the damages avoided when the atmospheric stock is reduced relative to the baseline.

Figure 2 Cumulative Reduction in Atmospheric CO_2 Relative to Baseline: 70 Million Ton Policy, Infinite Half Life



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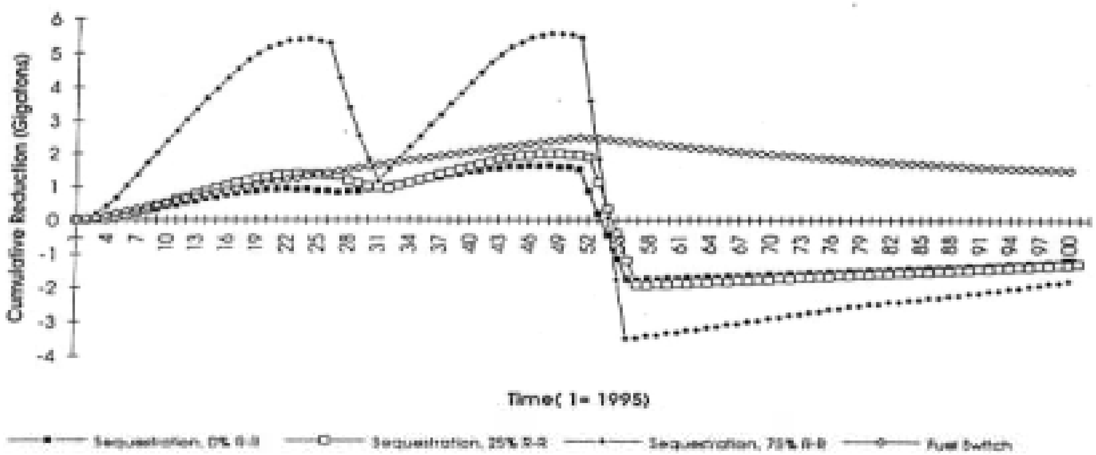
[6] The baseline amount of atmospheric CO_2, i.e., the amount of the atmospheric stock that would occur in the absence of any policy intervention, was calculated as the average of the three scenarios presented in Cline (1992a).

Figure 3 **Cumulative Reduction in Atmospheric CO_2 Relative to Baseline: 70 Million Ton Policy, 50-Year Half Life**



Benefit/Cost Analysis of Policy Options

The benefits of reducing the rate of accumulation of atmospheric CO_2 are measured as the avoided damage costs resulting from such a policy. Most estimates of the economic costs of damages attributable to global warming are based on an assumed doubling of the atmospheric concentration of CO_2 equivalents and a concomitant 2.5 degree (C) increase in global mean temperature. To simplify this analysis it was assumed that sequestration would be limited to carbon emissions. Cline estimated that the annual damages resulting from a doubling of atmospheric CO_2 (as opposed to CO_2 equivalents) would be $61.1 billion. [7]

Two forms of the damage function were examined—a linear form and an exponential form. With the linear form, the marginal cost of each additional unit of carbon that accumulates in the atmosphere is constant—however, it is much more likely that the damage function is not linear, and instead increases at an increasing rate. As such, the likely effect of the assumption of a linear damage function is to overstate damages in the near term and understate damages that occur in later years, when CO_2 concentrations exceed the doubling of current levels.

In order to assess the potential longer-term effects of such policies, it was assumed that each of the policies would be terminated after 50 years. Thus, beginning in year 51, all of the carbon that had been sequestered was assumed to be re-released according to the time path described above. This assumption was incorporated to analyze the effects that an unanticipated re-release over the long run could have on the relative magnitudes of the short-run and longer-run effectiveness of sequestration policies. In the case of the fuel

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[7] Cline, W.R., 1992, *The Economics of Global Warming*, Washington D.C., Institute for International Economics.

switching policy, it was assumed that the proportions of coal and natural gas used to produce electricity would return to their pre-policy values.

The benefit/cost analysis results of the carbon sequestration and fuel switching policies are summarized in Tables 2 and 3. The results are interesting in a number of respects. First is the fact that, over both a 50- and a 100-year time frame, none of the policies would yield positive net benefits. These results become more dramatic as the discount rate is increased from 0% to 5%. The fact that costs exceed benefits under all of the scenarios is explained, in large part, by the nature of the damage function. In particular, damages occurring as a result of global warming over the next 50 years would be small relative to the damages associated with a benchmark doubling of atmospheric CO_2.

A second point is that the assumed form of the damage function has a significant effect on the estimated benefits of a particular policy. In the case of sequestration policies, depending on the specific policy, benefits based on an exponential function are about 50% of what they would be if a linear function is assumed. This reflects the impact of two factors: (1) the form of the damage function on short-run avoided costs, and (2) the assumption that sequestered carbon is re-released at the end of the 50 year policy.

Table 2 Benefits and Costs of Alternative Carbon Policies: Infinite Half-Life (Average 70 Million Tons per Year, 1994$ Billions)

Re-release rate/ Discount Rate	Abatement Costs	Avoided Damages (Linear Fn)		Avoided Damages (Exponential Fn)	
		50 yrs.	100 yrs.	50 yrs.	100 yrs.
Sequestration					
0% Re-release					
0%	$58.6	$7.4	$8.3	$4.1	$4 .9
3%	$31.0	$2.9	$3.1	$1.4	$1.6
5%	$22.5	$1.7	$1.8	$0.7	$0.8
25% Re-release					
0%	$62.9	$8.8	$9.9	$4.8	$5.7
3%	$33.2	$3.5	$3.7	$1.7	$1.9
5%	$24.1	$2.1	$2.2	$0.9	$1.0
75% Re-release					
0%	$293.8	$20.6	$22.8	$10.6	$12.5
3%	$153.7	$8.7	$9.2	$3.8	$4.2
5%	$110.4	$5.4	$5.5	$2 .1	$2.2
Fuel Switching					
0%	$1,200.5	$7.0	$21.4	$3.9	$23.2
3%	$491.6	$2.8	$4.4	$1.3	$3.4
5%	$300.7	$1.6	$2.1	$0.7	$1.2

Table 3 Benefits and Costs of Alternative Carbon Policies: 50-Year Half-Life (Average 70 Million Tons per Year, 1994$ Billions)

Re-release rate/ Discount Rate	Abatement Costs	Avoided Damages (Linear Fn)		Avoided Damages (Exponential Fn)	
		50 yrs.	100 yrs.	50 yrs.	100 yrs.
Sequestration					
0% Re-release					
0%	$58.6	$4.1	($1.4)	$1.6	($3.4)
3%	$31.0	$1.7	$1.1	$0.6	$0.1
5%	$22.5	$1.0	$0.8	$0.3	$0.2
25% Re-release					
0%	$62.9	$5.2	(0.7)	$1.9	($3.2)
3%	$33.2	$2.2	$1.5	$0.7	$0.2
5%	$24.1	$1.3	$1.2	$0.4	$0.3
75% Re-release					
0%	$293.8	$14.3	$5.4	$4.8	($2.9)
3%	$153.7	$6.3	$5.4	$1.8	$1.0
5%	$110.4	$4.0	$3.8	$1.0	$0.9
Fuel Switching					
0%	$1,200.5	$5.4	$13.3	$2.1	$8.5
3%	$491.6	$2.1	$3.1	$0.7	$1 .5
5%	$300.7	$1.3	$1.5	$0.4	$0.6

Note: this result does not apply in the case of the fuel switching policy. This is because, unlike the sequestration policies considered (in which the sequestered carbon is assumed to be re-released after 50 years), fuel switching yields a stream of benefits into the indefinite future, regardless of whether the policy is permanent or only temporary. Because fuel switching reduces the amount of CO_2 *emitted* relative to the baseline, the future atmospheric stock of CO_2 is reduced relative to the baseline amount. Thus, there is some amount of avoided damages in perpetuity.

A third point to note is the relatively small increase in estimated benefits of carbon sequestration policies when the time period is increased from 50 to 100 years. This small increase is once again the result of assuming that the sequestered carbon is re-released once the policy ends. Depending on the half-life of excess atmospheric CO_2, this re-release would offset near-term avoided damages to a greater or lesser degree.

In the case of fuel switching, benefits increase by amounts ranging between 15% and 500% depending on the assumed form of the damage function, the assumed half-life of CO_2, and the discount rate. This outcome is the direct result of the fact that the emissions reductions resulting from fuel switching have a permanent effect on ambient CO_2 concentration levels. With respect to the range of benefits that might be attributable to sequestration policies, note that benefits associated with fuel switching are roughly equal to the benefits that would occur under a sequestration policy with 0% re-release after each growing cycle and no-release at the end of the policy.

Conclusions

Implementation of a reforestation program to sequester some amount of excess atmospheric CO_2 has received considerable attention as a potentially viable policy option. Estimates of the costs associated with such policies suggest that this strategy would be more cost-effective than a fuel switching policy that affects a comparable amount of CO_2 emissions. However, estimates of the relative benefits and costs associated with such policies also suggest that these same policies would be economically inefficient.

Going from an assumption of infinite half-life for atmospheric CO_2 to a 50-year half-life would serve to reduce the benefits of both types of policies. Thus, net benefits would decline as well. In addition, as the re-release rate for sequestered carbon is increased, the costs of carbon sequestration increase more rapidly than the benefits. As such, if a sequestration policy is adopted, it is important to maintain a low re-release rate.

In order to put these conclusions into the proper perspective, a number of points are worth noting.

> First, the benefits estimates presented are relatively small, in large part, because of the assumed relationship between the existing stock of atmospheric CO_2 and the damages attributable to excess atmospheric CO_2. In particular, the damage function reflects the assumption that the amount of damages associated with each unit of carbon emitted to the atmosphere is dependent on the existing stock of atmospheric CO_2. Thus, the damages avoided in the near term as a result of a reduction in atmospheric CO_2 are relatively small.
>
> Second, once a positive discount rate is applied to the estimates of benefits and costs, the effects of the manner in which the sequestered carbon is managed (i.e., the amount that is re-released) diminish considerably. This is largely attributable to the effect that discounting has on values that occur far into the future (e.g., 50 years and beyond).
>
> A third point to consider is that the benefits estimates presented in this paper are limited to estimates of damages attributable to global warming that would be avoided as a result of implementing one of the proposed policies. Additional potential benefits, such as the value of lumber that would be produced from mature trees as they are harvested, as well as other potential benefits could also result from such policies. Whether these additional benefits would be large enough to alter the conclusions of the analysis presented here is unclear.

A final point to consider is that the benefit estimates presented are confined to the avoidance of damages that would occur in the United States. In fact, a reduction in the amount of atmospheric CO_2 would provide some amount of benefit to the rest of the world as well. Whether such benefits should be included in an assessment of a policy that would be implemented in the United States, and presumably paid for by the citizens of the United States, is a matter for policymakers to debate. In any event, the benefit estimates reported are likely to be an understatement of the benefits that would be realized on a global scale. Depending on the magnitude of these additional benefits, the conclusions presented above could be reversed.