# A Brief Overview of Carbon Sequestration Economics and Policy

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For the past dozen years there has been a growing interest in the possibility of mitigating the global warming effects of carbon dioxide by increasing the carbon stocks of biomass and soils. The earliest economics studies examined the costs of capturing and storing carbon in forest ecosystems (for a review of these studies see Richards and Stokes 2000). Over time, the potential for cost-effectively storing carbon on agricultural lands has also emerged as a focus of research (Lal et al. 1998; Antle et al. 2002). Through the course of the research on carbon sequestration and policy two themes have emerged. First, because of the nature of the analyses it has been difficult to compare the results of the many studies that report estimates of the cost of carbon sequestration in terms of dollars per ton. Second, it appears that it will be more difficult to implement a market-based large-scale carbon sequestration program than many had imagined. These two issues have led to significant confusion in the discussions of carbon sequestration economics and policy. In fact, the two issues are intertwined. It is impossible to meaningfully model the costs of a carbon-sequestration program absent a careful description of how the program would be implemented.

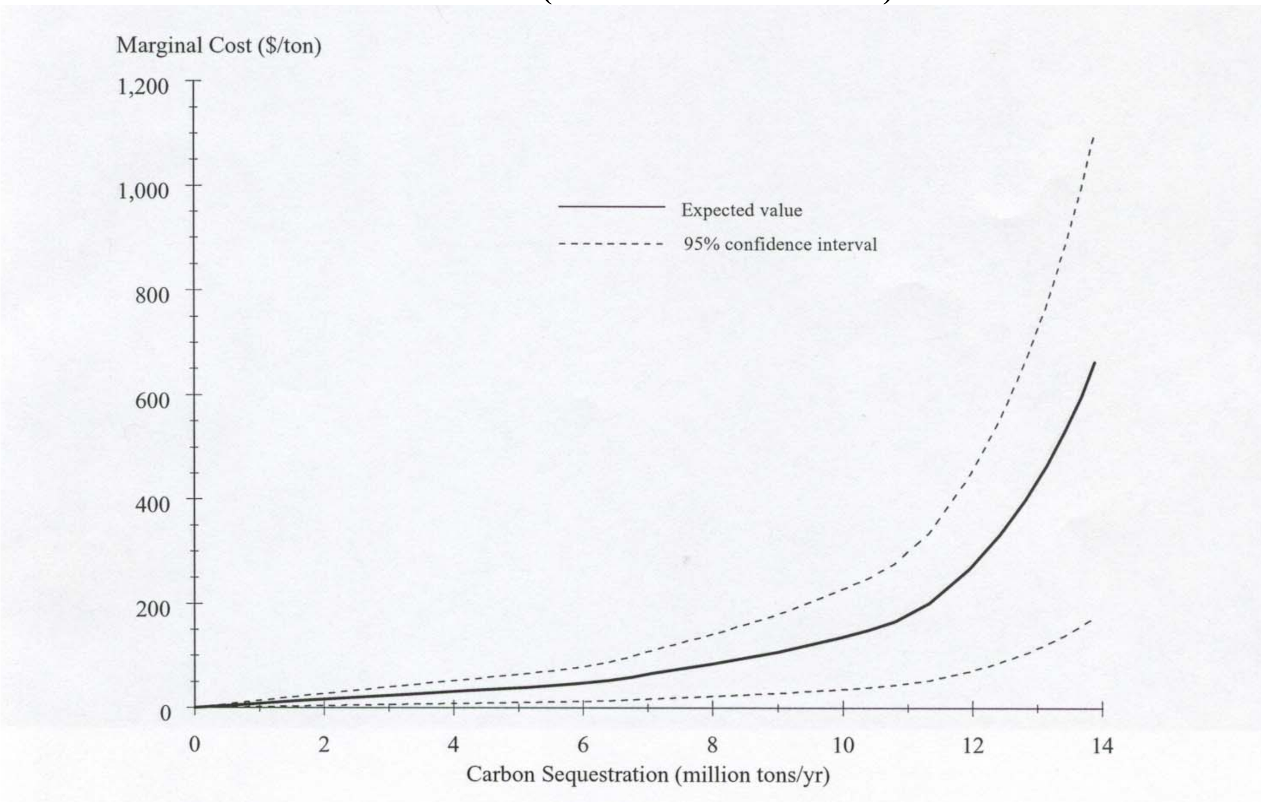
The purpose of this paper is to provide an overview of the issues and challenges involved in analyzing the costs and program design for carbon sequestration. While the focus is on forest carbon sequestration, many of the observations apply to sequestration on agricultural lands as well. Similarly, many of the issues are couched in terms of implementing a domestic carbon sequestration program, but apply equally well to the design of an international program.

The discussion is divided into two parts. The first section examines some of the pitfalls of comparing the results of carbon sequestration cost studies and suggests some simple ways in which analysts could make their results more useful. It also highlights three areas in carbon sequestration cost estimation where additional research would be particularly useful. The second section of the paper reviews issues related to the implementation of a carbon sequestration program, including which policy tools are available and which have received the most attention, some of the challenges for using those policy tools, and one alternative that has received little attention, but may become necessary. The final section of the paper provides conclusions.

## Cost Studies

The earliest works in carbon sequestration economics focused on estimating the cost-effectiveness of the sequestration option, specifically to examine whether expansion of forest sinks could play a major role in the effort to slow the accumulation of atmospheric carbon dioxide. In general, these studies each follow a similar pattern: they posit a government program such as subsidies, government purchases, or contracts, to promote a particular forest practice such as afforestation of agricultural land, modification of forestry management practices, or preservation of forestland, for a particular geographic context, which can vary in scope from sub-national to global. With the outline of the hypothetical program roughly in place, the analyses proceed to attach costs to the various inputs to production including land, labor, and materials.

**Figure 1: Marginal Cost Of Carbon Sequestration for Periodically Harvested Pine Plantation in the Delta States (Newell and Stavins 2000).**




In general these studies have suggested that there are substantial opportunities for sequestering carbon in forests, perhaps on the order of 500 millions tons per year in the United States alone. But the cost estimates for achieving these high levels of sequestration range over two orders of magnitude, approximately from 5 to 500 dollars per ton. This rather large range of costs exists in part because the analyses are based upon different hypothetical programs. One would expect different programs to have different costs. However, there are several other more subtle differences among the studies that lead to different costs estimates, some of which make comparisons among the studies problematic.

**Model Type**

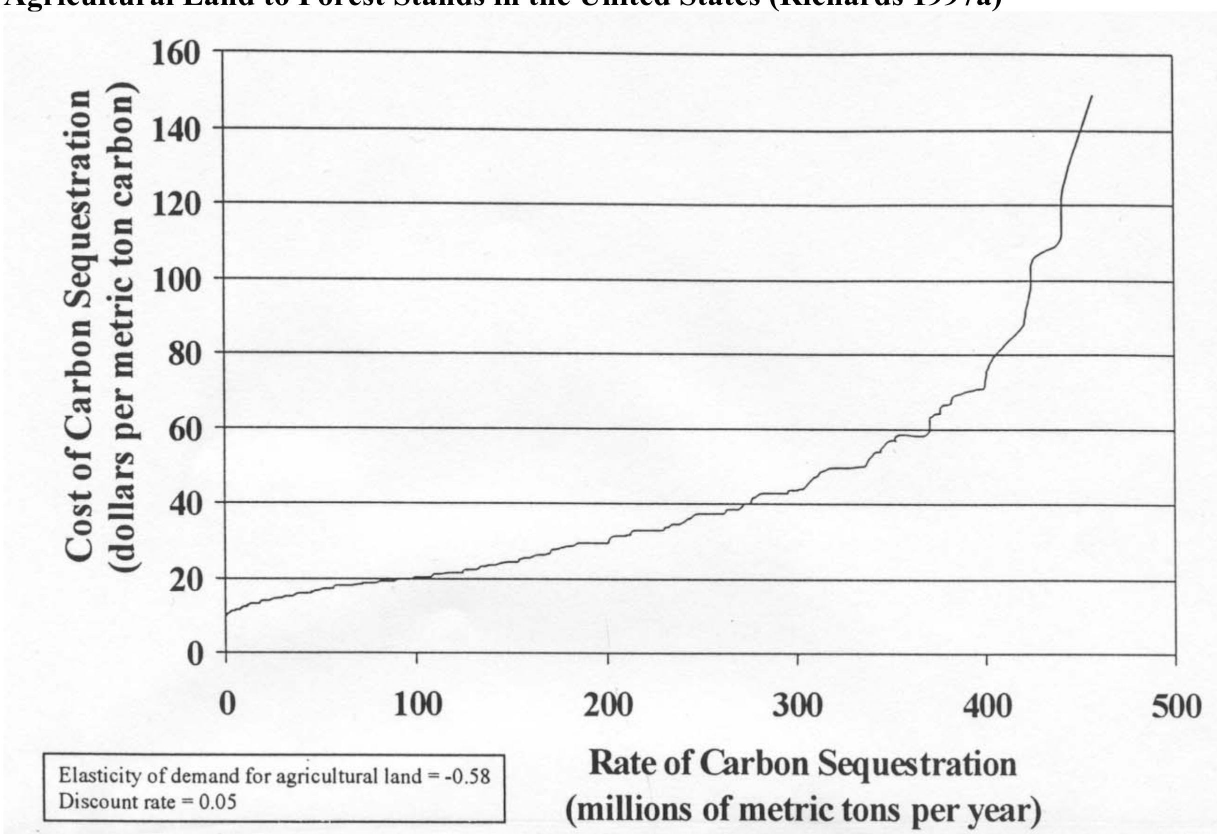
The first factor that differentiates cost studies is the type of model that is used to estimate the opportunity costs of land. There are three basic types of models. Bottom-up or engineering models generally use reported land prices to estimate the social cost of converting land from one use or practice to another Dudek and Le Blanc 1990; Moulton and Richards 1990; New York State 1991; Richards et al. 1993; Richards 1997a; Sedjo and Solomon 1989; van Kooten et al. 1992). These models are generally limited in scope to the immediate on-site effects of a program or practice.

Sectoral models estimate the opportunity cost of land based on supply and demand equations for the agriculture or forestry sectors (Adams et al. 1993, 1999; Alig et al. 1998; Sohngen and Mendelsohn 2001; Sohngen et al. 1998). The costs of various programs and practices are derived from estimates of changes in consumer and producer surplus as the amount of land dedicated to agriculture or forestry expands or contracts. Those sectoral models that combine agriculture and forestry sectors are able to include the effects of the competing demands of the two sectors for land.

Econometric studies use historic market responses to changes (generally in timber prices) that are analogous to a government carbon sequestration program to infer how landowners would respond to direct or indirect carbon prices (Kerr et all 2001; Newell and Stavins 2000; Plantinga and Mauldin 2000; Plantinga et al. 1999; Stavins 1999). Because the models capture both the ebb and flow of forestland as prices for forest products (timber or carbon) change, they inherently capture the interplay between agriculture and forest lands.

Each of these types of models has different strengths and weaknesses. The bottom-up models tend to be simple and transparent, but generally include no concessions for friction in the market or interactions between sectors. The sectoral and econometric models provide more insight into the dynamics of market interactions. The sectoral models may be less data intensive than the econometric models, based as they are on existing supply and demand equations, but they do not account for landowner reluctance to change land uses, a fundamental conservatism. In general, econometric studies seem to provide higher estimates of carbon sequestration costs, while the bottom-up models provide lower estimates because they account for less of the overall counteracting results.

**Figure 2: Marginal Cost Curve for Carbon Sequestration by Conversion of Marginal Agricultural Land to Forest Stands in the United States (Richards 1997a)**




**Types of Costs**

Another reason for the apparently large range of cost estimates, even under similar conditions, is that studies are providing estimates of different types of costs. Some studies provide only point estimates of costs, corresponding to specific carbon sequestration targets. Others provide cost curves, corresponding to a range of carbon sequestration levels and generally demonstrating the expected upward sloping curves. Even among those that provide cost curves, however, there is significant variation because they may be estimating one of three different types of costs – total cost, average cost, or marginal cost – expressed as a function of annual, cumulative, or present equivalent sequestration levels (see next section). This is a total of nine possible types of cost curves, none of which can be directly compared to the others.

In general, there seems to be an emerging consensus that curves expressing marginal costs as a function of equivalent annualized sequestration levels are the most useful for comparing across analyses of mitigation options, but there is still no universally accepted format (see Figures 1 and 2 for examples of marginal cost curves). For now the consumer of the results of sequestration cost studies is best advised to exercise caution when comparing the results of studies.

**Definition of "Dollars per Ton"**

A more subtle problem for comparing the results of studies is that they do not all use the same metric for cost-effectiveness, i.e., "dollars per ton". While virtually all the studies use either a present or annualized value of costs (numerator), studies have employed at least three different definitions of what a ton is (denominator). This in turn leads to three different definitions of dollars per ton.

The first method for calculating cost-effectiveness is the "flow summation" approach, which defines tons in the denominator of the metric as the total flow of carbon throughout the life of the project or program. Under this approach there is no discrimination among tons according to when they are sequestered. A ton captured one hundred years in the future has the same weight as a ton captured this year.

In comparison to the flow summation approach, the "average storage" method uses a denominator that expresses the average amount by which storage of carbon in the study area increases. Thus it is a stock rather than a flow measure. Moreover, the average storage method implicitly assumes that there will be some form of harvest leading to cyclical variations in carbon storage levels. It also assumes that there is a finite period of time over which the average increment in storage can be measured. Unlike the flow summation approach, the average storage method does differentiate between carbon that is captured earlier and carbon that that is captured later; carbon captured earlier in a cycle has more time over which to contribute to the average increase in stocks.

The "levelization/discounting" approach is a flow-based metric that discounts the weight of tons more heavily as they occur further in the future. One way of conceiving this is that the levelization/discounting method assumes that the marginal value of sequestering a ton of carbon is constant over time, so that the present value can be discounted in the same way as any other economic benefit. If the levelization/discounting method is used with a zero discount rate on carbon it produces the same result as the flow summation method.

The choice among these three metrics can make as much as an order of magnitude difference in the resulting cost estimates. Thus it is quite misleading to compare the results of studies that have used different metrics. Of the three, the levelization/discounting approach seems to be emerging as the standard. First, as a policy matter the flow summation method is fundamentally flawed because it does not differentiate according to when sequestration takes place. Implicit in this formulation is the assumption that it does not matter when sequestration takes place. If that is the case, then the cost-effectiveness of any program can be improved by delaying commencement for a year and investing the funds for the project in an alternative use at a positive interest rate. The delay in carbon capture would have no cost but would have a benefit in the form of increased funds available. If a delay of one year is good, a delay of several is better, and in fact there is no reason to start the project. In short, if it does not matter **when** the carbon is captured then it does not matter **whether** it is captured.

Second, the average storage method is only applicable to a limited project type, i.e., those with cyclical changes in carbon stocks. In contrast, the levelization/discounting approach can be adapted to any pattern of carbon sequestration. Third, most studies of emissions reductions from the energy sector implicitly use the levelization/discounting approach so this method facilitates comparison with a broader range of studies.

**Emerging Issues**

For the reasons described above, the consumer of carbon sequestration cost studies must be cautious about directly comparing estimates of cost-effectiveness from different studies. The consumer should also be aware that there are several emerging issues that require additional attention.

Most studies concentrate on the costs of practices to protect and expand carbon sinks. Few have included the possible secondary benefits, which could be accounted as "negative costs" in the standard analysis of carbon sequestration cost-effectiveness. Yet there is evidence that the secondary benefits of some carbon sequestration practices, particularly conversion of marginal agricultural land to forest stands, could be as great as the costs of the conversion. Thus in a cost-effectiveness study, carbon sequestration might be nearly costless. Clearly, this issue deserves substantial additional attention as it may drive the cost curve down and possibly even into a negative range over some levels of carbon sequestration.

In contrast to the secondary benefits issue, the effects of leakage may substantially raise the costs of carbon sequestration. "Leakage" occurs when the effects of a program or project lead to a countervailing response beyond the boundary of the program or project. This problem arises from two basic facts. First, land can be shifted back and forth among various forestry and agriculture uses. Second, the balance of activities on land will depend upon the relative prices in the agriculture and forestry sectors, and individual projects and programs do little to change those prices or the resulting demand for land. For example, if forestland is preserved from harvest and conversion in one location, the unchanged demand for agricultural land and forest products could lead to increased forest clearing and conversion in another region. Thus the effects of the preservation may be partially or entirely undone by the leakage. Similarly if agricultural land is converted to forest stands, the underlying demand for agricultural land may simply cause other forested land to be converted back to agriculture.

There are a growing number of studies that address the issue of leakage. Alig et al. (1997) demonstrated that this countervailing pressure is serious enough that the accomplishments of a national carbon sequestration program could be largely dissipated over several decades as existing forestland is converted in response to rising agricultural land prices. Stavins (1999) addressed this issue in his econometric model of the Delta States by allowing land conversion to occur in both directions, depending upon the relative rates of return on investment in the two uses. Sohngen, Mendelsohn and Sedjo (1998) also demonstrated that the problem has a transboundary aspect. Because the timber market is global in scope, forest protection and expansion programs in one part of the world can be counterbalanced by market responses in other regions.

The third emerging issue, impacts on systems of public finance, arises from outside the work of carbon sequestration cost studies. In general, it is expected that a carbon sequestration program would be implemented with different policy instruments than a carbon emissions abatement program. If carbon sequestration is either subsidized or used as an offset against carbon taxes or auctioned marketable allowances, then it will have quite a different affect on the system of public finance than an emissions control mechanism. Compared to a quota (tradable or otherwise) on carbon emissions, a carbon sequestration subsidy requires raising revenue. Similarly, allowing a carbon sequestration offset against a carbon emissions tax or auctioned allowance will reduce the amount of revenue raised by the mitigation program.

The recent public finance literature (Goulder 1997; Goulder et al. 1997, 1998; Parry 1995a, 1995b, 1997a, 1997b, 1998) has examined the differential impact of various government instruments used to implement environmental policy. In general, those instruments that require revenue-raising such as subsidies and contracts have a higher social cost than those that raise revenue, such as auctioned marketable allowances and emissions taxes. This effect relates back to the fundamentally distorting effect of revenue-raising itself. Thus if carbon sequestration is implemented in a way that requires more revenue-raising than emissions abatement, it will have an additional cost that has not been reflected in any of the cost studies, one that could be extremely important in any comparing the relative costs of carbon sequestration and emissions reduction.

All three of these emerging issues suggest three directions for research on the costs of carbon sequestration. First, estimating the full costs of carbon sequestration programs will be advanced by including the secondary benefits, if any, of the practices under consideration. Second, analyses will also be more useful as they include more of the interactions among the affected sectors – agricultural, forestry, energy and public. This suggests the need for more general equilibrium analyses. Expanding research in this direction will provide a better understanding of both the leakage issues that may dissipate the accomplishments of carbon sequestration programs and the differential effects on the system of public finance that will likely increase the costs of carbon sequestration relative to other options. Finally, to facilitate advances in the first two directions, models of carbon sequestration program costs need to be more explicit about the mechanism design that will be used to implement large-scale carbon sequestration programs.

It is this last point, policy implementation, to which the discussion will now turn.

## Policy Implementation

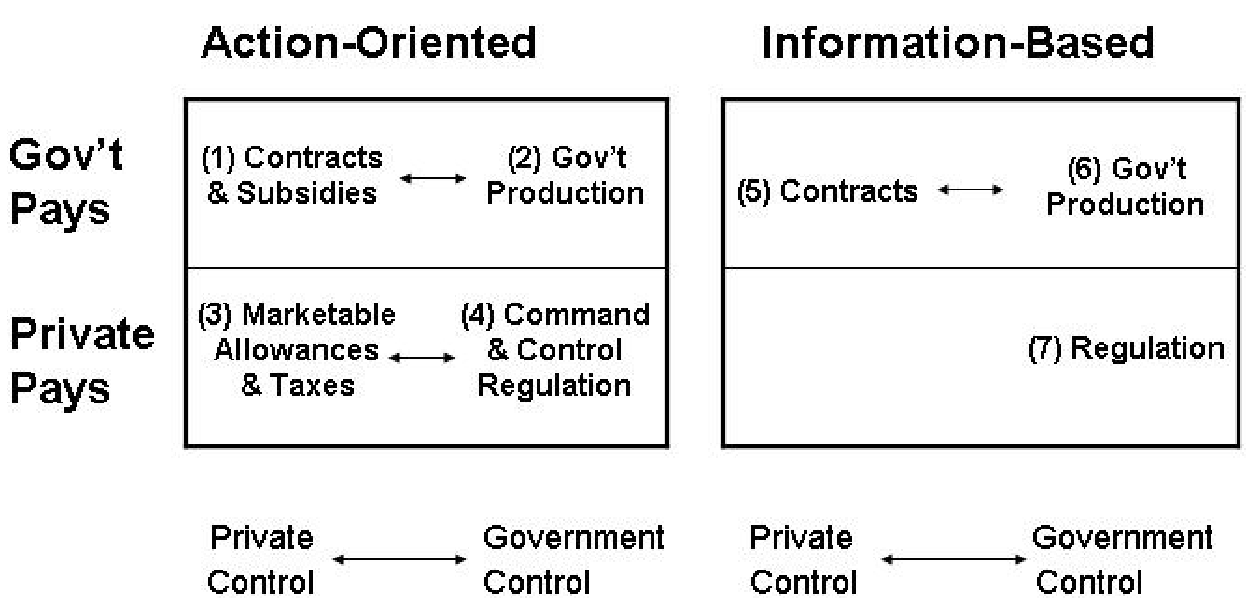
Where cost-effectiveness analyses dominated research on carbon sequestration economics initially, there has been increasing attention to program design issues. This section of the review will develop a framework for considering the policy implementation problem. The discussion will start by providing a conceptual framework and a brief look at some of the approaches that Congress has considered for promoting carbon sequestration. With the benefit of both the conceptual framework and the overview of legislative initiatives, the discussion will turn to the challenges and issues related to the various alternatives.

**Conceptual Framework**

If the government wants to promote carbon sequestration, what are the policy tools available for the task? To help organize the government's tool chest consider the following three dimensions along which the various policy instruments can be differentiated (Richards 2000).

1. *Action-orientation versus information-oriented.* This dimension addresses the fundamental purpose of the government program. In some cases the government addresses the external effects of pollutants, in this application carbon dioxide, directly by constraining emissions or by providing incentives to decrease emissions. So the government might place a quota on emissions or provide subsidies for sequestration. In other cases the government attempts to improve the information regime by promoting research, developing new technologies, educating the public, and providing technical assistance. Information-oriented approaches address the public-good nature and scale-economies of information by generating and disseminating information.
2. *Who pays?* The instruments can also be distinguished according to who pays for their implementation. Implicit in the use of subsidies, standard contracts, and direct government production is the assumption that the government will bear some or all of the financial burden of the environmental improvement or information task. Under these approaches private parties participate voluntarily for the benefit of the incentives provided by the government. Under other instruments such as marketable allowances, emissions taxes, and command-and-control regulation, the regulated party pays for the cost of mitigation. Under these instruments, private party participation is coerced, i.e., not voluntary.
3. *Discretion.* Some instruments such as marketable allowances, emissions taxes, and output-based subsidies are designed to vest control over the mitigation practices in

**Figure 3: Types of Policy Instruments**



private sector parties. In their purest form, these instruments provide rewards based on the final product, e.g. the amount of carbon emissions reduced or offset, leaving the means of achieving the outcome entirely to private parties. Other instruments restrict private discretion, instead vesting control in the government, either as it carries out abatement activities directly through its agencies or controls private actions through specific legislation and rules. In addition to these either/or arrangements, there are a multitude of discretion-sharing and control mechanisms under which the government provides some but not complete discretion to private parties.

Simply recognizing these three dimensions to government action allows us to develop a simple framework for examining Congressional proposals and organizing the discussion of carbon sequestration options. With respect to carbon sequestration, the government can induce private parties to enlist in a program to protect and expand sinks – area (1) in Figure 3 - by either offering to pay any landowners who sign up a pre-specified price in terms of dollars per ton (subsidy), or by setting a sequestration goal and negotiating with landowners for the best prices (contracts). These are price-based and quantity-based approaches, respectively, and are both designed so that the rewards are directly proportional to the output, i.e., the amount of incremental carbon sequestered.

Alternatively, the government could choose to produce sinks directly (2), presumably using its own land resources and perhaps renting or buying additional lands. Under this approach the Department of Agriculture might provide the forestry and agricultural expertise, aided by laborers supervised by agency officials. As with the contract and subsidy approaches, the government bears the cost of the activities under direct government production, but also retains control over the process by which the sequestration takes place.

Between these two extremes are many control-sharing mechanisms. For example, the government might pay landowners to sequester carbon, but restrict the range of practices that can be used. Alternatively, the government and private parties could undertake cooperative ventures with shared decision-making responsibilities.

The government can also coerce cooperation from reluctant parties. In the area of emissions abatement, the federal government has used tradable allowances to control sulfur dioxide emissions, and state governments have used fees to discourage the generation of hazardous waste (3). Certainly, both of these mechanisms have been considered for controlling carbon dioxide emissions. It is more of a stretch to imagine how these instruments might be used in the carbon sequestration application, though there have been proposals to tax carbon dioxide emissions from certain land areas just as they would from fossil fuel energy sources. The government can also use the familiar regulatory approach (4) that controls what landowners are allowed to do with their carbon sinks.

The government can use a similar though somewhat narrower range of instruments to generate and disseminate information. For example, the government can contract for information generation (5) in the form of commissioned R&D, provide technical assistance directly through it own agencies (6) such as the agricultural extension service, or compel the development of management plans and studies (7) as many states do with forest harvesting and replanting programs.

In concept the government could use any one or combination of these instruments to implement a carbon sequestration program. The next section examines which instruments have been the focus of congressional activity.

**Congressional Bills**

A review of the bills introduced into the two chambers of the U.S. Congress over the past two sessions (four years) reveals that there have been more than 50 uniquely numbered pieces of legislation directly or indirectly addressing carbon sequestration in that time. Table 1 provides an example list of legislation. While there is significant overlap and duplication among the bills, they still cover a wide range of concepts and approaches including 1) early crediting systems, 2) tax incentives for carbon sink projects and R&D, 3) grants for research on biofuels, project monitoring and measuring, and remote sensing of carbon cycles, 4) managing carbon on federal government lands, 5) public education, and 6) subsidized loans for flexible fallow practices and management and protection of forests.

Table 1: Examples of Bills Related to Carbon Sequestration from 106$^{th}$ and 107$^{th}$ Congress

| **Title** | **Citation** | **First Sponsor** |
|---|---|---|
| The Energy and Climate Policy Act | 106 S. 882 | Murkowski |
| Carbon Cycle and Agricultural Best Practices Act | 106 S. 1066 | Roberts |
| Climate Change Tax Amendments of 1999 | 106 S. 1777 | Craig |
| Domestic Carbon Storage Incentive Act of 2000 | 106 S. 2540 | Brownback |
| Credit for Voluntary Actions Act | 106 H.R. 2520 | Lazio |
| Conservation Security Act of 2000 | 106 H.R. 5511 | Minge |
| Carbon Sequestration Tax Credit Act | 107 S. 765 | Brownback |
| International Carbon Conservation Act | 107 S. 769 | Brownback |
| Carbon Sequestration and Reporting Act | 107 S. 1255 | Wyden |
| Emission Reductions Incentive Act of 2001 | 107 S. 1781 | McCain |
| Conservation Tax Incentives Act of 2001 | 107 H.R. 2290 | Portman |
| National Greenhouse Gas Emissions Inventory Act | 107 H.R. 4611 | Olver |

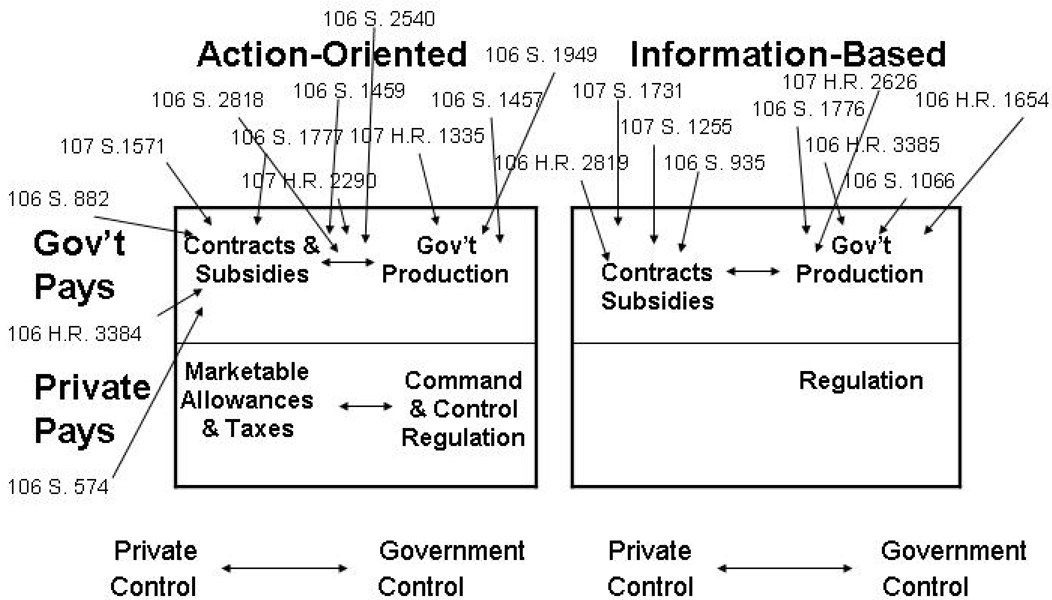
Figure 4 illustrates which policy instruments have been incorporated in an admittedly nonrandom but hopefully representative selection of the proposed legislation from the past four years. The figure suggests that Congress has largely concentrated on the non-coercive instruments of contracts, subsidies, and government production, or some combination thereof. In fact there are three primary approaches discussed in the policy literature, considered by the Bush Administration, and reflected in Congressional proposals.

1. *Incentives for Output*: This market-based approach provides incentives in direct proportion to the incremental amount of carbon sequestration a participant provides. The incentives may be dollars under a subsidy or contract, a tax credit or deduction, or an offset allowance against an emissions cap. Currently, the Administration and several Congressional proposals envision a voluntary program under which current carbon sequestration activities would earn tradable credits that could be used as an offset against future mandatory emissions reductions. This approach foreshadows the possibility of an eventual government-backed offset program linked to either a cap-and-trade or a tax program on the emissions side. Underlying much of the public discussion of sinks is the assumption that we will eventually have a pure market-based approach to carbon sequestration.
2. *Incentives for Activities*: This approach restricts incentives to practices that have been selected by the government. For example the government might provide subsidies for

certain forest management practices or contracts for flexible fallow activities. Rather than paying for an output (carbon) the government pays for a readily observable input. In doing this the government retains control over which sequestration practices will be recognized.

3. *Government Production*: The government can also produce sinks on land it already owns, or land it purchase or leases for this purpose. This provides the government with still more control than providing incentives to private landowners for activities, but limits the locations to federally controlled lands. It also gives up the high-power incentives of the market-based approaches.

Figure 4: Policy Instruments Incorporated in Congressional Proposals



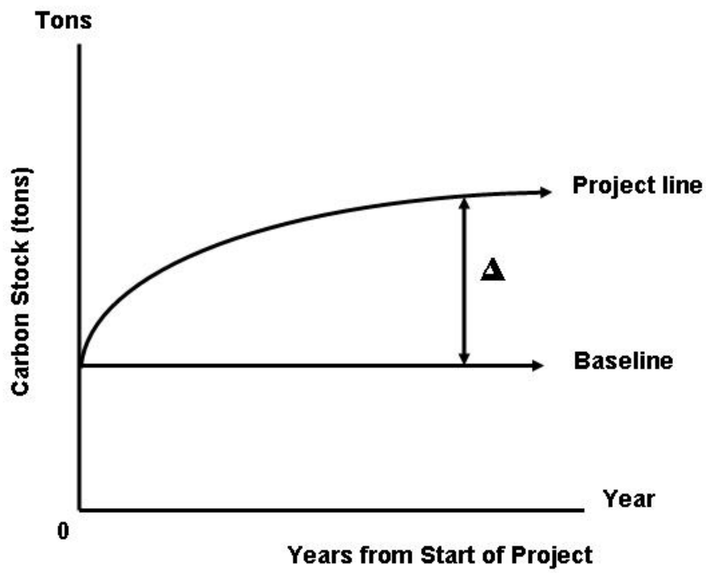

The government must determine which of these three approaches is best suited to the carbon sequestration application. In general, the market-based solutions that give the most freedom for innovation to landowners might be expected to minimize the cost of producing carbon sinks. However, often times it is more efficient to move away from market-based approaches such as outcome-based contracts and subsidies. This is particularly the case when 1) the output is not easily measured, 2) when the goal of the program or policy is complex or subject to change over time, or 3) when the government can not credibly commit to sustain the reward system over the relevant time horizon. Are these issues that raise concerns about a pure market-based approach relevant in this case? The next sections address this question.

**Measurement of Carbon Sequestration from Individual Projects**

There are two primary issues related to measurement that must be addressed. The first issue relates to measuring carbon on the site of the project. Fundamentally, to evaluate the carbon effects of a project it is necessary to compare what would have happened to carbon stocks or flows without the project (*reference case*) to what did happen or would happen with the project (*project case*). The difference between the two cases, call it **Δ**, provides a measure of the effects of the project. The project case can be observed in the field and measured, albeit at some cost, in many cases with a high degree of confidence. The reference case, however, can not be directly observed for the simple reason that it did not happen, i.e., it is a counterfactual case. Rather it must be inferred through one of several means (Richards and Andersson 2001).

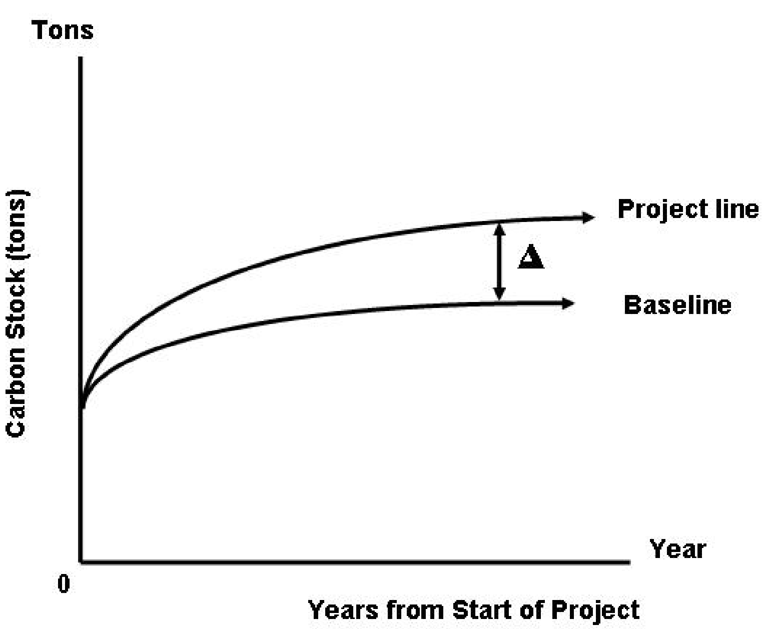
The first type of reference case assumes that everything within the boundary of the project would have remained the same over time. There would be no changes in carbon stocks from either natural or human influences (Figure 5). For example, the analysis of projects that convert farmland to forest stands is often based on an assumption that the carbon level in the cropland soils was static and that the land would have continued to be farmed in the absence of the project. In this case, the baseline carbon level in the reference case can be projected from the levels of carbon stock at the beginning of the project.

Figure 5: Simple Baseline (Type 1)



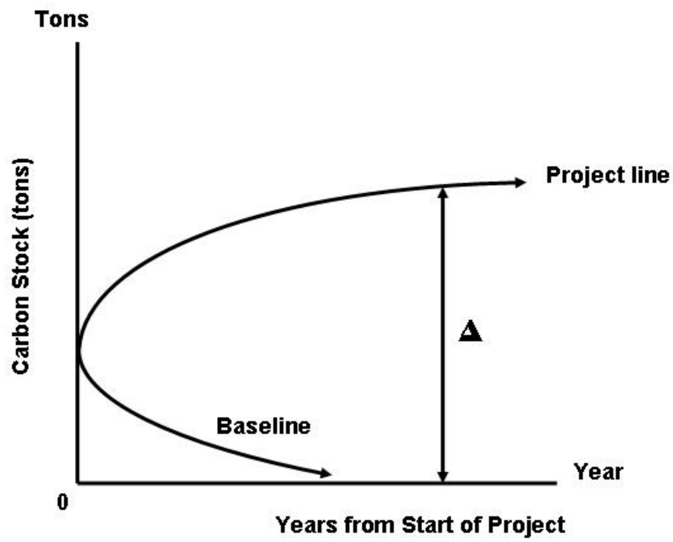

The second type of reference case is based on the assumption that there would have been changes in the carbon stocks due to natural processes only (Figure 6). Change in human activities would not have changed carbon levels. In these cases it is possible to infer the baseline carbon stock in the reference case through models of natural processes or by use of control groups. Typically the reference case carbon stocks would be rising, as in the case of projects involving improved management of naturally regenerating forest areas.

Figure 6: Dynamic Baseline (Type 2)




The third type of reference case arises when the project is based on an assumption that human activity would have somehow changed carbon stock levels, generally in a negative way (Figure 7). Typically this is the kind of assumption that underlies forest preservation projects. At the project level the baseline in these cases is largely based on conjecture about the nature, extent and timing of the avoided activities. A number of the projects reported in the 1605(b) database are based on these types of conjectural reference cases. The problem is that these activities tend to be rather idiosyncratic with respect to an individual project site so there is a large margin of error. More worrisome, perhaps, is the fact that creative story tellers may be able to manufacture carbon storage more easily by lowering the carbon stocks in the reference case than by increasing the carbon stored in the project case. Note, of course, that both of the other types of reference cases are conjectural in as much as they are based on the assumption that there would have been no human intervention – a conjecture in and of itself.

Figure 7: Conjectural Baseline (Type 3)




Researchers and project developers have spent a great deal of effort and resources refining the measurements and estimates of project case carbon – i.e., the carbon that can be observed. But the final result, **Δ**, is the difference between project carbon levels and reference case carbon levels. It is not clear that expending significant resources to narrow the confidence interval around the estimation of the project carbon level is necessarily a good investment of resources if there is substantial uncertainty associated with the reference case carbon level.

The second issue related to carbon sequestration measurement relates to off-site changes attributable to the project, what is commonly referred to as leakage. As described above in the discussion of cost studies, leakage occurs when the project activity has the effect of changing offsite behavior in a way that dissipates some or all of the carbon sequestration activity. For example, in the case of a project that protects a particular area from harvest, an analysis that focuses solely on the amount of carbon on the protected site will miss countervailing activities offsite, such as increased harvest on other sites. The net amount of harvest, agriculture, forestland, cropland, and pasture are determined at least in part by the market demands for forest and agricultural products. Often, changes in one part of the system will induce compensatory changes in other parts.

There are some carbon sequestration-enhancing activities that may have little effect on the supply of market goods, and hence induce little leakage. Flexible fallow and modified harvesting techniques may be able to increase carbon stocks while not affecting the supply of agricultural and timber products. There may also be cases where the heterogeneity of land quality or other important factors is such that there are opportunities for projects that have little or no effect on the market. This might be the case for some projects converting marginal agricultural land to forests. However, the number of projects that would not affect the market is certainly limited, if in fact there are any. With a sequestration program of any size, it will be important to account for the leakage effect.

It is unclear how serious the reference case and leakage effects are. Do they threaten the viability of a market-based approach? One measure of the feasibility of estimating the effects of carbon offset projects is whether the results are independently reproducible. Given that so much rides on the future of a large-scale carbon sequestration program, it might be reasonable to check this attribute. One way to do that is to assemble a teams of acknowledged experts in the field of carbon project evaluation, develop a portfolio of, say, a dozen carbon sequestration projects of various types, perhaps drawn from the 1605(b) database, and have each of the teams evaluate the portfolio independently. The results would be informative. They would indicate which types of projects are subject to the greatest variance in evaluation. Comparison of the analyses would provide insight into which types of effects led to the most variance in methods. And it would illustrate how different groups of analysts dealt with different types of uncertainty. To my knowledge, no such exercise has been conducted.

**Other Factors in Program Design**

It was stated above that 1) measurability of individual project results, 2) the level of uncertainty in, and the complexity of, the goal and execution of a sequestration program, and 3) the government's ability to credibly commit to maintain incentives over long periods of time, all might be factors in assessing whether a pure market approach is preferable to the options under which the government retains more control over the type and manner of sequestration projects that are undertaken. The discussion above suggests that at least for some types of projects, measurement of project results could present an obstacle to using the market approach. What about the other criteria?

There is indeed significant uncertainty about the science of carbon sequestration and the ways in which human intervention and changes in land use will affect the carbon cycle. Moreover, a carbon sequestration program is likely to pursue multiple goals that include erosion control, habitat provision, timber supply, and recreational enhancement. Thus, the goals of a sequestration program are likely both to be difficult to measure and to shift over time.

For many types of projects the benefits accrue over a period of decades, in many cases achieving peak uptake rates only after 20 to 40 years. Landowners who make these investments will no doubt want to know whether the government will still be rewarding carbon sequestration long into the future as their activities come to fruition. It is unclear whether the Federal government will be able to make credible commitments to provide stable incentives over long periods of time. In general, subsidy programs are subject to frequent revision. Perhaps by using long-term contracts the Federal government can establish a commitment to continue rewards over the entire life of sequestration projects.

Combined with the difficulty in measuring the carbon sequestration attributable to an individual project, the uncertainty inherent in carbon sequestration and the challenges of credible commitment, suggest that the government should at least consider the policy tools – government production and contracts with shared discretion – under which it retains some control over, and bears some of the risk of, the sequestration process.

There are other issues related to program design as well. For example, exactly what carbon sequestration event will the government reward? If the government chooses an output-based approach it could pay for carbon capture (measured in tons), or for carbon storage (measured in ton-years). These two approaches can be made to mimic each other in financial terms, but they have very different implications for implementation. Administratively, paying for storage, sometimes called "carbon rental", is the easier approach. There is an annual payment proportional to the average size of the carbon stock over the period of the year. If the carbon stock is drawn down (i.e., there is a release of carbon), the size of the annual payment decreases. In contrast, when there is a payment for carbon capture, and implicitly permanent storage, the government must also make some provision for recouping payments when carbon is released.

Whether this recovery of payments upon release is carried out through normal contractual remedies or other mechanisms specified by the program, the process of collecting payments from landowners who release carbon is likely to involve substantial administrative and legal costs.

The primary disadvantage of the carbon rental approach is that it substantially delays the payments that landowners will receive. Even paying for carbon capture spreads payments over several decades adding another element of risk to the investment from the landowners' perspective. Paying for storage would delay payments substantially further, likely raising the perception of risk, and consequently the payments required.

Regardless of whether the government uses one of the incentive-based approaches or undertakes public provision of carbon sink expansion, it will be necessary to identify a discount rate to apply. The discount rate determines the relative value of a ton of carbon reduction in the atmosphere today versus one a year, ten years, or even one hundred years in the future (Newell and Stavins 2000; Richards 1997b). For the purpose of designing rewards, the discount rate will determine the value of a ton-year versus a permanent ton of storage, and the relative values of either of those metrics to the value of a stream of expected tons of capture and storage associated with a new project such as tree planting on agricultural land. The lower the discount rate, the lower will be the value of a ton-year of storage relative to a permanent ton of storage.

### The Regulation Instrument

In all three of the implementation approaches discussed above, including government production, there are serious issues related to leakage. Given that the agricultural and forestry sectors are connected through a single land supply, and land use patterns are determined at least in part by the market demand for agricultural and forestry products, projects that change land use or affect the supplies of products will likely involve some level of leakage. In many cases increasing carbon sequestration in one area will be accompanied by a countervailing decrease in another. To develop a coherent carbon sequestration program, the government is going to have address this issue.

It may be possible to deal with leakage simply by making carbon storage payments to all landowners with substantial carbon stores. This will lead owners to consider the consequences of land conversion among agriculture, forest, and other uses. The value of changes in carbon storage will be "internalized". It is likely, however, that this will be a very costly approach from the perspective of the government funds required.

Consider some arguably analogous programs where the federal government has addressed land use and conservation issues: wetlands, species and habitat protection, and coastal zone management. In each case the government has directly employed, or induced states to implement, regulatory approaches to restricting the loss of important land-related conservation functions. It might seem odd, indeed, if the government pursued a policy of increasing the total amount of wetlands in the country by paying people to construct and restore wetlands, but did not simultaneously restrict the destruction of existing wetlands. Such a policy might well eventually lead to a situation where the only remaining wetlands have been constructed in anticipation of government payment. All natural wetlands would disappear.

Similarly, if the government decides to pursue an aggressive carbon sequestration program, it may have to face the unpalatable choice of either regulating the conversion of existing carbon sinks as it has done for wetlands, species and habitat preservation, and coastal zone management, or paying all landowners who hold substantial carbon sinks to induce them not to release their carbon stores in response to mounting market pressures for land. Clearly, however, before the government could follow either of these paths, there would have to be a far greater degree of public concern and political pressure than the issue of mitigating greenhouse gas emissions now receives.

**Conclusions**

This paper has attempted to provide a brief overview of the economics and policy issues related to terrestrial carbon sequestration. A few points merit highlighting.

Over the past dozen years or so there have been a number of studies that analyzed the costs of carbon sequestration. During that time it has been necessary to clarify several analytical issues such as the definition of "dollars per ton" and differences in the underlying models and types of costs that have made it difficult to compare the results of studies. As this area of research progresses studies should attempt to address the interplay, and particularly leakage effects, among carbon sequestration programs and the agriculture, forestry, and energy sectors, the implications of public finance and revenue-raising for the costs of carbon sequestration relative to emissions control, and the importance of instrument choice in determining the efficiency with which carbon sequestration policies are implemented. Use of more general equilibrium modeling should help accomplish these goals. The secondary benefits and costs of expanded sinks also warrant additional attention as these effects may substantially change the total social costs of carbon sequestration.

On the policy side, much of the attention reflected in research and in Congressional and administrative initiatives has been focused on preparing for and implementing markets for carbon offsets. However, the discussion above suggests that given the characteristics of many sequestration activities – difficulty measuring outputs, scientific and programmatic uncertainty, high initial investment costs for projects, potential concern with the level of government commitment to the program – the approaches under which the government retains more control over the sequestration process may be warranted. This would require, however, a significantly greater commitment of resources by the government than it provides under the current or anticipated approaches that focus on the private sector.

Finally, if carbon sequestration becomes a major component of an aggressive greenhouse gas mitigation policy, the government is going to have to squarely face the issue of how to address the issue of leakage. Two options, neither politically or economically palatable, are universal coverage of all sinks with a system of subsidies for storage or a regulatory system that limits landowners' rights to modify their lands in a way that leads to large releases of carbon.

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