

## **Is There a Role for Geologic and Terrestrial Carbon Sequestration in Greenhouse Gas Mitigation?<sup>1</sup>**

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The scientific consensus that global climate change is happening and a serious threat to human welfare is increasing the likelihood that meaningful policy actions will be considered in the United States and elsewhere, including a renewed international agreement to replace or extend the Kyoto Protocol. In this paper I discuss the role for geologic and terrestrial carbon sequestration in the mix of options that could contribute to reductions in atmospheric concentrations of the major greenhouse gases.

Carbon dioxide (CO<sub>2</sub>) is the most important greenhouse gas, accounting for about 77 percent of the increase in warming potential observed. Increases in atmospheric CO<sub>2</sub> have been caused by a variety of human activities, principally fossil fuel combustion (about 82 percent) and land use change (about 18 percent). Despite recent increases in the price of oil, coal and oil remain abundant and relatively cheap compared to renewable sources of energy, accounting for about 80 percent of current energy consumption. Known reserves of oil are estimated to be sufficient for at least 50 years, while coal reserves are thought to be sufficient for more than 200 years. But global consumption is rising rapidly, particularly in the developing countries. China alone is currently bringing on line the equivalent of two 500 megawatt coal-fired power plants each week, adding

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coal use equivalent to the entire UK electricity consumption each year (Ansolabehere et al., 2007).

Barring some unanticipated major breakthrough in energy technology, fossil fuels will continue to be the most important source of energy for the foreseeable future. This fact suggests that if economic growth is to continue while greenhouse gas emissions are reduced, it will be necessary to capture the carbon released from fossil fuel combustion and permanently store it. This process of capturing and permanently storing carbon is called carbon sequestration.

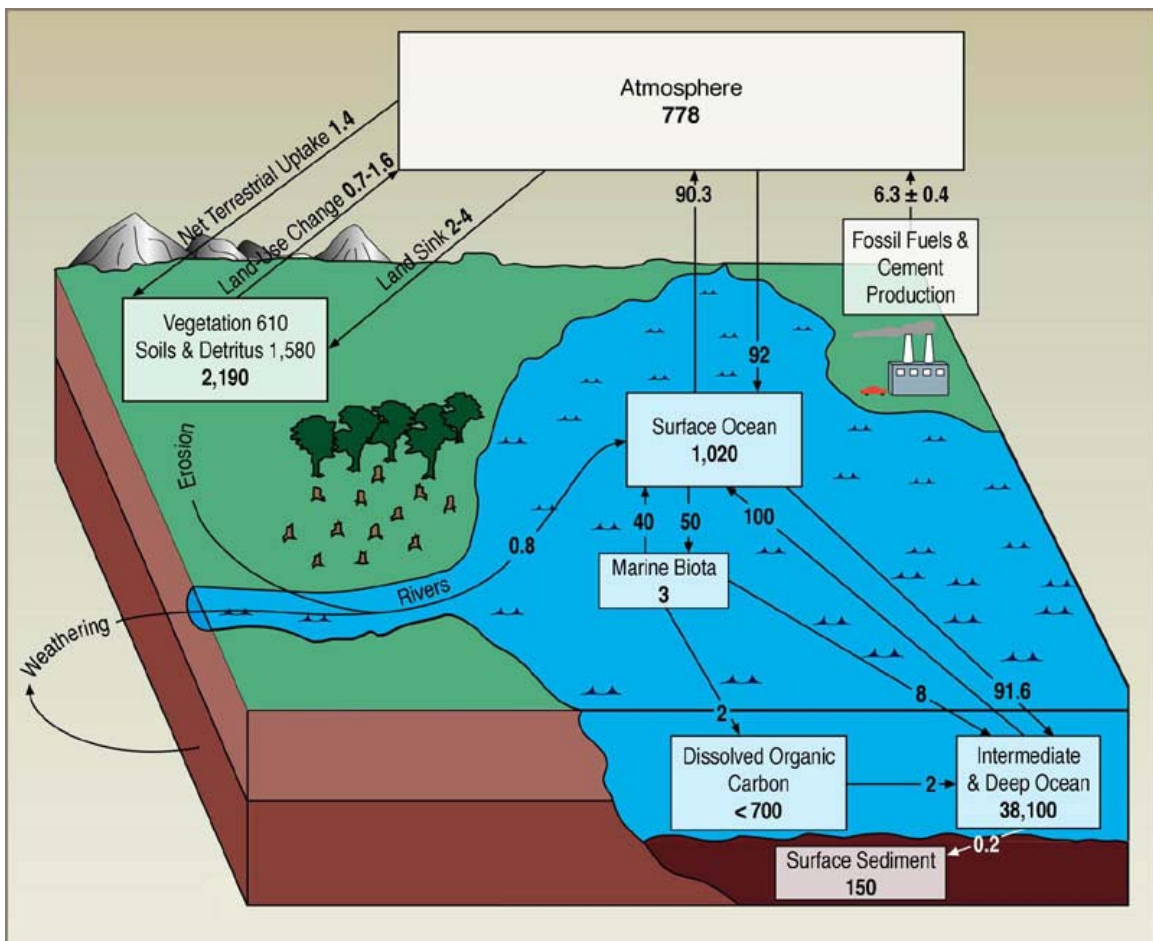


Figure 1. Natural and anthropogenic components of the carbon cycle (Source: US Climate Change Science Program, 2003).

As Figure 1 shows, the global balance of carbon in the atmosphere is dependent on a number of natural and anthropogenic processes. Fossil fuel use for power generation and transportation are the largest source of additions to atmospheric CO<sub>2</sub>, but land use change also makes a substantial contribution through processes such as deforestation and the disturbance of soils through agricultural production and non-agricultural activities such as road construction. For example, conversion of undisturbed grasslands in temperate climates such as the central United States to agriculture is estimated to release about half of the carbon stored in topsoil over 30-50 years.

Given the current state of science, carbon sequestration can operate principally through two types of processes, terrestrial and geologic. Terrestrial sequestration is based on the fact that plants take CO<sub>2</sub> out of the atmosphere through photosynthesis and store it as organic carbon in above-ground biomass (trees and other plants) and in the soil through root growth and the incorporation of organic matter (Figure 2). Thus, the process of carbon loss through land use change can be reversed, at least partially, through improved land use and management practices. In addition to afforestation, changes in agricultural land management, such as the adoption of tillage practices that reduce soil disturbance and incorporate crop residues into the soil, can remove carbon from the atmosphere and store it in the soil as long as those land use and management practices are maintained.

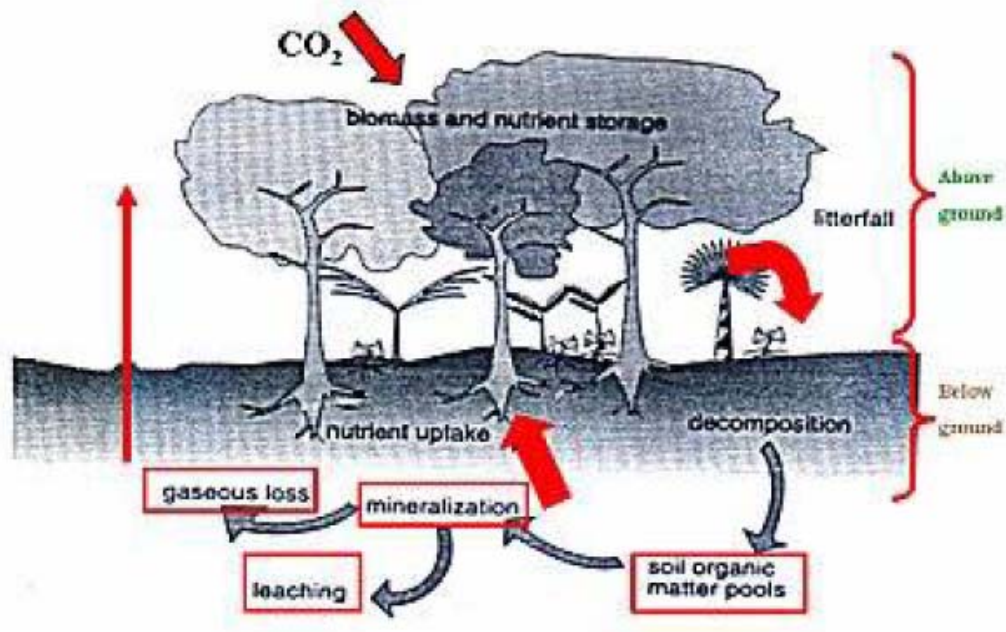


Figure 2. Terrestrial sequestration in above-ground biomass and below ground in soil.  
 (Source: Food and Agriculture Organization,  
<http://www.fao.org/ag/agL/agll/carbonsequestration/background.stm>)

The alternatives to terrestrial sequestration involve capturing CO<sub>2</sub> from power generation and other industrial processes and converting the carbon into a form that can be stored for a long period of time (Figure 3). While options such as ocean storage have been discussed, geologic sequestration is the option that appears to be the most technically and environmentally viable. CO<sub>2</sub> is already being collected and re-used in processes such as enhanced oil recovery which involve the transport and injection of CO<sub>2</sub> to increase the extraction of oil and gas from depleted reservoirs (so-called enhanced oil and gas recovery). CO<sub>2</sub> can be removed from flue gasses of conventional electric power generating plants using known technology, and new technology such as coal gasification is being developed that will allow CO<sub>2</sub> to be captured and stored more efficiently. A number of options exist for storing CO<sub>2</sub>, including injection into deep saline aquifers,

basalt rock formations and depleted oil and gas wells. Using CO<sub>2</sub> for enhanced oil and gas recovery also provides a potential sequestration option, although further research is needed to investigate the permanence of storage when it is used for this purpose.<sup>2</sup>

The purpose of this paper is to introduce the principal technological options for carbon sequestration, assess their economic feasibility, and discuss related policy options. The first section highlights the concepts of technical and economic feasibility that are critical in understanding the potential for carbon sequestration to contribute to reductions in greenhouse gas emissions. The following sections address major issues related to terrestrial and geologic sequestration, drawing on recent research in the two fields. The chapter concludes with a discussion of policy options to advance the implementation of carbon sequestration as a part of a larger greenhouse gas emission reduction strategy.

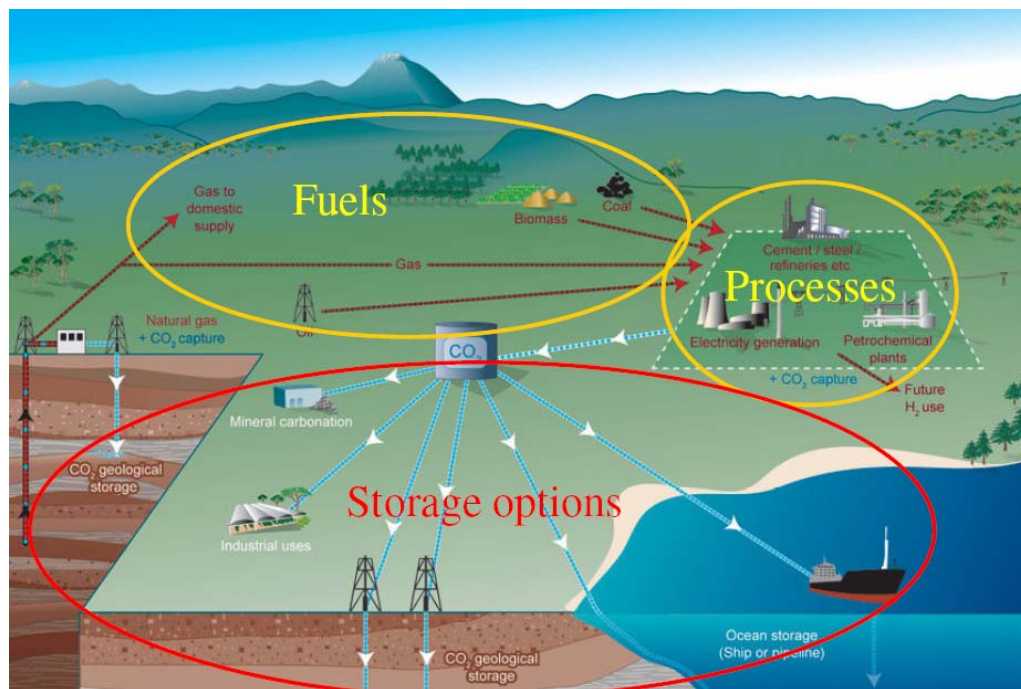


Figure 3. Carbon Capture and Sequestration Options (Source: Metz et al., 2005)

<sup>2</sup> For a useful overview of carbon capture and storage options, see Metz et al. 2005.

## Technical and Economic Potential for Carbon Sequestration

There are a number of ways to reduce greenhouse gas emissions, including direct regulatory intervention and the use of incentives such as a carbon tax or a cap-and-trade system. We now know that incentive-based approaches to environmental regulation are more efficient than command-and-control regulation in most cases. One reason for the efficiency of incentive-based regulation is that the cost of reducing emissions per unit of emissions reduction varies greatly from one emissions source to another. This variability in cost is particularly true for carbon sequestration. This spatial variation in sequestration efficiency is due to two sets of factors.

First, the *technical potential* for sequestration varies from place to place. Technical potential is the maximum amount of carbon that can be sequestered at a site (either in soils or biomass, or injected in a geologic formation) regardless of cost. Technical potential varies across locations for terrestrial sequestration because of differences in soils and climate that impact the biological processes involved. Similarly, technical potential for geologic sequestration varies with the type of geologic formation, the depth of the injection required, the distance from the CO<sub>2</sub> source, and so forth. When we sum up all the quantities that can be sequestered at each site in a region, we obtain the technical potential for the region.

Second, the *economic potential* for sequestration is also highly spatially variable. The economic potential is defined as the amount of sequestration that is profitable for economic agents to undertake at a site or in a region, and is embodied in the *carbon supply curve* which shows the quantity of carbon that would be sequestered at given

prices for carbon. In the case of terrestrial sequestration, farmers may choose to participate in a contract that pays them a specified price for each ton of carbon they sequester in their soil or by planting trees in place of crops. However, in order to sequester more carbon in the soil, they must make costly changes in their management practices, as discussed further below, or they must forgo crop production if they plant trees. Therefore, the economically motivated farmer will enter such a contract only if the price for sequestering carbon is high enough to make participating in such a contract more profitable than the farmer's best alternative use of the land would be.

### *Terrestrial Sequestration Potential*

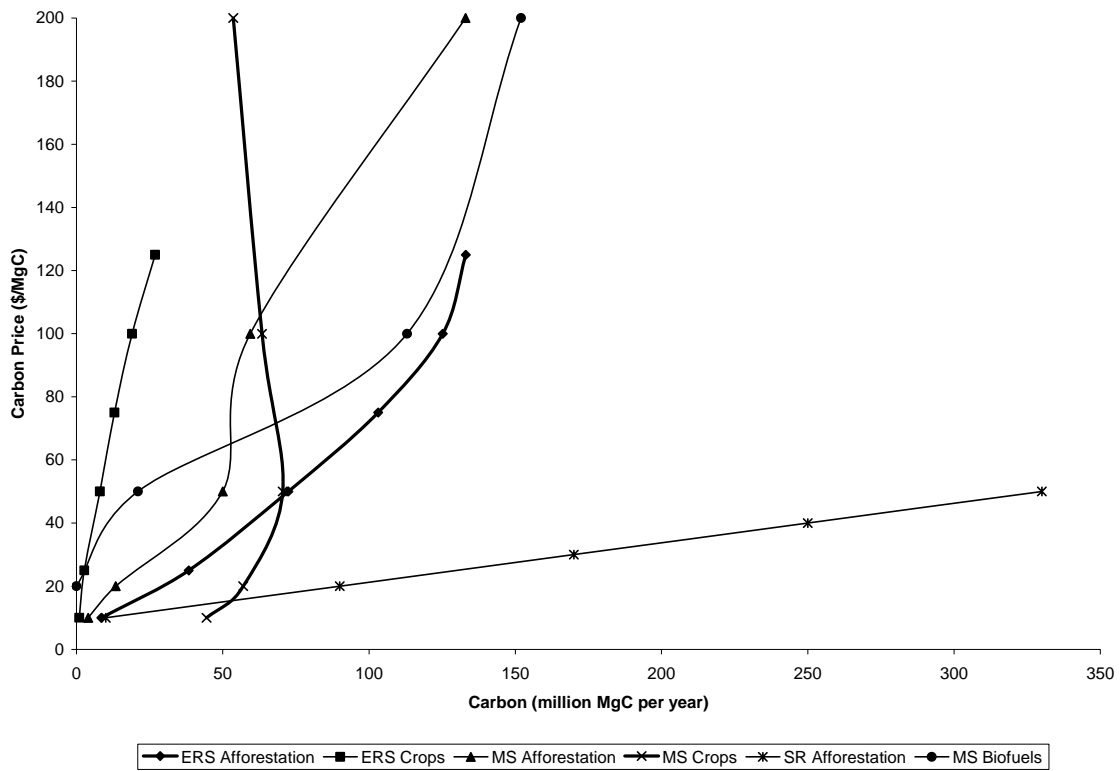
Recent studies have summarized what is known about technical and economic potential for the two major terrestrial sequestration options in the United States, afforestation and agricultural land use and management changes (Stavins and Richards, 2005; Paustian et al., 2006). Results from several of these studies are summarized in Figure 4. While the different studies use different data and models and make a variety of different assumptions, these studies nevertheless provide at least a sense of the order of magnitude of carbon sequestration potential over a plausible range of carbon prices.<sup>3</sup> This figure shows that over a reasonable range of carbon prices --- up to about \$125/megagrams of carbon (a megagram of carbon, MgC, equals 1000 kilograms, or one metric tonne) --- the estimated maximum cropland potential for carbon sequestration is in the range of 25 to 70 million MgC per year<sup>4</sup>. Afforestation has a higher potential according to

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<sup>3</sup> Studies of carbon sequestration options through reductions in industrial emissions show that if there were meaningful emissions reductions on a global scale, the likely range of carbon prices would be \$25 to \$200 per MgC (Antle and McCarl, 2002). The recently established carbon market in the EC has seen carbon prices in the range of \$50 to \$100 per MgC. Note that the recent prices on the Chicago Climate Exchange are lower than the level in the EC because the United States does not yet have a legal limit on emissions.

<sup>4</sup> In this chapter carbon quantities are stated in metric tons and denoted MgC (million or mega grams of C). It is important to be aware that carbon quantities and prices are often quoted in metric tons of CO<sub>2</sub> as well.

these studies, but again there is a wide range of estimated economic potential. One key factor in the large difference between the Stavins and Richards supply curve for carbon sequestration services in Figure 3 and the ones from the ERS and McCarl and Schneider studies is the assumption about technical potential for afforestation in the Great Plains region where there is a large amount of relatively low-value rangeland and cropland that could possibly be converted into tree plantations. The Stavins and Richards supply curve was derived from a study which assumed a relatively high potential for trees to be grown in the Great Plains region, despite the fact that the region is relatively dry and trees historically have not been extensively grown naturally or in tree plantations. The ERS and McCarl and Schneider studies assumed a much smaller potential for tree growth in the Great Plains region.



The molecular weight of CO<sub>2</sub> is 3.67 times that of C alone, thus 1 MgC is equal to 3.67 metric tons of CO<sub>2</sub>. To convert prices, note that if the price of carbon is \$100/MgC then the equivalent price per metric ton of CO<sub>2</sub> is \$100/3.67 = \$27.25.

Figure 4. US Carbon Sequestration Supply Curves for Afforestation and Croplands (Paustian et al., 2006). (ERS = USDA Economic Research Service, MS = McCarl and Schneider, SR = Stavins and Richards). (Source: Paustian et al. 2006).

The studies mentioned in Figure 4 are all based on the principle of opportunity cost, and simulate farmers' participation in carbon contracts by comparing the profitability of carbon sequestration with the profitability of alternative types of land use. In addition to the opportunity cost of changing land management, there may be a variety of other factors that impact farmers' and other land owners' willingness to participate in carbon contracts (Paustian et al., 2006). For example, uncertainty about the returns to the carbon-sequestering management practice may increase the price managers require to be willing to enter a contract (thus effectively shifting the carbon supply curve leftward to some degree). In addition, negotiating, setting up and monitoring carbon contract agreements may itself be expensive<sup>5</sup>.

#### *Geologic Sequestration Potential*

Carbon sequestration involves several steps as illustrated in Figure 3, including capturing the CO<sub>2</sub>, transporting it to the storage site, and then putting it into storage. In geologic sequestration each of these steps involves specific technology and corresponding capital investment. As Figure 3 shows, geologic sequestration involves extracting CO<sub>2</sub> from a stream of industrial gas emissions, such as the flue gases of a coal-fired power plant, converting it to a form suitable for transport (typically through a pipeline), and injecting it into the geologic formation. In addition to what is shown in Figure 3, there are likely to be significant costs associated with monitoring geologic

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<sup>5</sup> Antle et al. (2007) show that these "transaction costs" may also substantially shift carbon supply curves to the left, particularly at low carbon prices.

sequestration sites to ensure that the CO<sub>2</sub> does not leak beyond permitted rates, as well as with regulatory compliance and liability insurance.

To date very little economic research has been conducted on geological sequestration, and consequently there are very large uncertainties related to the potential costs of geologic sequestration. The principal source of cost information at this time is research carried out at the Massachusetts Institute of Technology, where an interdisciplinary study of coal use for electric power generation was carried out (Ansolabehere et al. 2007). This study utilized a set of simulations of typical coal-using power plants to estimate the costs of capturing CO<sub>2</sub>. The results indicate that the capture cost component may be in the range of \$32 to \$55 per metric ton of CO<sub>2</sub>, which is equivalent to about \$115 to \$200 per MgC. The MIT study and other analysts have estimated that the costs of transport and injection are likely to be approximately half of the capture costs, although these costs will vary significantly depending on the volume of CO<sub>2</sub> transported and injected, the terrain that has to be crossed, and the characteristics of the injection site. Using this range of numbers, it can be concluded that the cost may be in the range of \$170 to \$300 per MgC. Although there have not been any studies to construct carbon supply curves for geologic sequestration comparable to the terrestrial studies presented in Figure 3, we can conclude that the carbon supply curve for geologic sequestration will begin at a level that is likely to be in the range of \$150 to \$200 per MgC, and will likely increase to \$300 per MgC or higher beyond some point as the lower-cost alternatives are exhausted. Figure 5 presents a possible carbon sequestration supply curve constructed using the data from the MIT study together with some simple

assumptions about the types of technologies that would be utilized by existing coal-fired power plants and investments in new plants.<sup>6</sup>

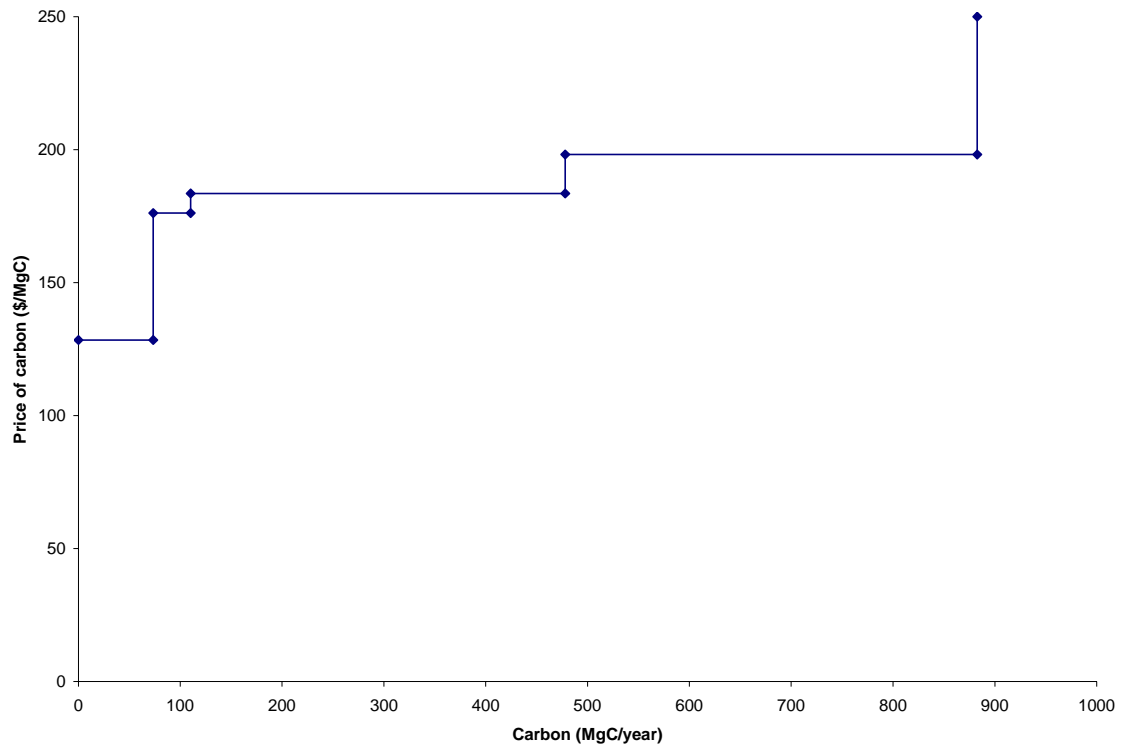


Figure 5. Possible Geologic Carbon Sequestration Supply Curve for the United States (Source: author's calculations based on data from Ansolabehere et al. 2007).

### *Comparing Terrestrial and Geologic Sequestration*

We can see from the above discussion that terrestrial and geologic sequestration each have their advantages and disadvantages, and differ in important ways in how each of these components is carried out. In terrestrial sequestration, the problem is greatly simplified in the sense that capturing CO<sub>2</sub> is solved by plants and trees through photosynthesis, the carbon is stored at the point where it is captured, and it is stored in

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<sup>6</sup> Specifically, it was assumed that there are 1000 existing plants, 900 currently using subcritical processes and 100 using supercritical processes. In addition, it was assumed that 100 new plants would be built with coal gasification technology. Further details are available from the author.

biomass or soil. The principal action required to increase the amount of carbon captured and stored is related to land management at the site, and it can usually be implemented with minimal capital investment and uses well-established technology. Terrestrial sequestration has several other positive attributes. First, it removes CO<sub>2</sub> from the atmosphere, and could result in a net reduction in the concentration of CO<sub>2</sub> in the atmosphere, and can offset emissions from any sources, either a point source such as a power plant or mobile sources such as motor vehicles. Second, there are environmental co-benefits from terrestrial sequestration. Afforestation is often associated with wildlife habitat, biodiversity conservation, and water quantity and quality improvements. Soil sequestration has positive impacts on agricultural productivity and water quality and quantity. Third, while monitoring and measuring terrestrial sequestration involves some costs, it has been shown to be relatively low-cost and there are no environmental risks associated with terrestrial sequestration. Since only small amounts of carbon are stored at any given site (say, a hectare of surface area), a failure of sequestration at any one site has little consequence. Therefore, the main legal or regulatory issues associated with terrestrial sequestration involve a standard contractual arrangement between the land owner and the entity paying for the carbon storage. However, there are other challenges with terrestrial sequestration, including transaction costs of establishing and verifying compliance with contracts, establishing additionality, and preventing leakage (offsetting actions that negate some of the benefits). Some analysts argue that these difficulties would offset any possible benefits, whereas others see these as minor obstacles that could be overcome when there is a policy providing adequate incentives for efficient contracting.

In contrast, geologic sequestration involves a number of industrial processes, several of which are relatively untested and require large capital investments. CO<sub>2</sub> must be separated from other gases in emission streams, concentrated into a form that can be efficiently transported to the injection site, and then injected into the geologic formation. One important limitation of geological sequestration is that it can only reduce CO<sub>2</sub> emissions from point sources (such as power plants), because as yet there is no commercially available technology to filter CO<sub>2</sub> out of the atmosphere once it has been emitted by mobile sources (such as cars).<sup>7</sup> Another critical aspect of geologic sequestration may be environmental risk, whether real or perceived. For example, it may be difficult to know the potential impacts of large quantities of injected liquid CO<sub>2</sub> on water quality and micro-organisms. There is also the possibility of a large amount of CO<sub>2</sub> leaking and posing health risks, based on events that have already happened, in which naturally occurring CO<sub>2</sub> leaked from underground sources and asphyxiated people. Even though this is a remote possibility, experience thus far with attempts by Department of Energy research programs to make test injections of CO<sub>2</sub> shows that there is likely to be strong public resistance to this idea. Furthermore, the legal and regulatory issues associated with transporting, injecting and storing large quantities of CO<sub>2</sub> are unclear and pose potentially high hurdles both in terms of institutional and legal liability as well as cost. Schemes for monitoring injection sites to ensure leakage conforms to legal requirements are only in the conceptualization stage and the costs of implementing them has not been studied (e.g., see the proposal in Ansolabere et al. 2007). However, many of

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<sup>7</sup> There have been some proposals for technologies that would filter carbon from free air but have not been implemented (e.g. Lackner, Grimes and Ziocck 2007). Another way to capture emissions from mobile sources could be to replace internal combustion vehicles with electric vehicles that use power from plants with carbon capture.

the environmental risk and regulatory issues might be avoided by geologic sequestration under the seabed, although costs of transportation and injection might be higher. Further research is needed to assess the tradeoffs between these alternative approaches.

A final key difference between terrestrial and geologic sequestration is in their technically and economically feasible capacities and the present state of knowledge and uncertainty about these capacities. A large and growing body of well-established science exists to support the technical and economic feasibility of terrestrial sequestration. This research shows that the technical capacity of terrestrial sequestration is potentially important but limited. For example, Paustian et al. (2006) estimate that the technical potential for terrestrial sequestration in the United States is in the range of 5-14 percent of the approximately 7.5 gigatons of U.S. carbon dioxide-equivalent greenhouse gas emissions.<sup>8</sup> As Figure 4 shows, most economic studies of terrestrial sequestration potential in the United States show that at plausible carbon prices, less than 200 million MgC are likely to be sequestered, which is less than about 10 percent of U.S. carbon dioxide-equivalent emissions.

In contrast, the technical potential for geologic sequestration in the US is relatively large, but highly uncertain. Current emissions from U.S. coal-fired power plants is estimated to be about 1.5 gigatons CO<sub>2</sub> per year or about 20 percent of total U.S. carbon-equivalent emissions. Geologic sequestration capacity estimates range from several gigatons to thousands of gigatons, but is likely to be at least several hundred gigatons. Thus, geologic sequestration has a likely technical potential to meet a large share, if not all, of the U.S. demand for sequestration capacity for the foreseeable future.

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<sup>8</sup> Carbon dioxide-equivalent emissions is calculated by combining all of the major greenhouse gases using weights based on their potential to impact global warming.

However, as noted above, very little economic research on geologic sequestration has been carried out so there are also large uncertainties about the economic cost and therefore feasibility of geologic sequestration. Figure 5 shows that, using the only available data, at a price of about \$200 per MgC (or a price of about \$55 per metric ton of CO<sub>2</sub>) it would be economically feasible to sequester about 1 gigaton of carbon per year, or about 3.67 gigatons of CO<sub>2</sub> per year, which is about 50 percent of total U.S. CO<sub>2</sub>-equivalent emissions.

### **Policy Implications**

To obtain a rough estimate of the total economic potential for carbon sequestration in the United States, the data from Figures 4 and 5 were combined into a national carbon supply curve for both terrestrial and geologic sequestration (Figure 6). This figure shows that at relatively low prices for sequestration (say, below \$50 per MgC, which is approximately the current price in the European market), only terrestrial sequestration options would be economically feasible and less than 200 million MgC would be sequestered (less than 10 percent of U.S. emissions). The amount sequestered would roughly double if the price of carbon were increased to about \$180/MgC. However, at that point the supply of carbon sequestration services would increase rapidly even without much further increase in price --- up to about 1400 MgC, or almost 70 percent of U.S. emissions --- as it became economically feasible to retrofit a substantial share of coal-fired power plants.

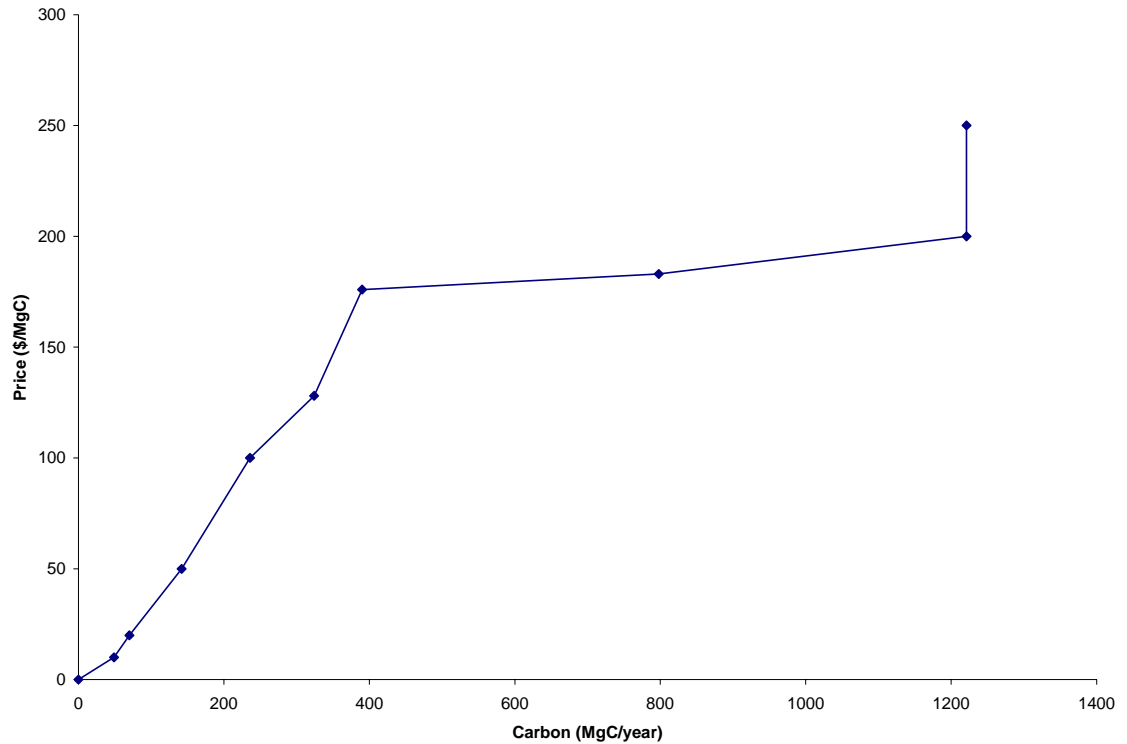


Figure 6. U.S. Carbon Supply Curve for Terrestrial and Geological Sequestration (Source: based on Figures 5 and 6)

Using the data in Figure 6, together with basic economic reasoning, we can reach a number of policy implications.

First, contrary to the claims by some that substantial efforts to reduce greenhouse gas emissions would seriously harm the US economy, current estimates indicate that imposing carbon sequestration costs on the order shown in Figure 6 would increase US electricity prices in the range of 2.5 to 4 cents per kilowatt hour (US Department of Energy, 2007). This compares to a current cost of electricity that ranges from about 6 to 18 cents per kilowatt hour in and average about 10 cents (US Energy Information Agency, 2007). The costs used to construct figure 6 and the impacts on electricity are based on current technology. Experience with other forms of pollution control technology

has shown that once there is a substantial economic incentive to reduce emissions, costs of pollution control have been reduced dramatically. For example, today the cost of removing pollutants such as sulphur dioxide from flue gases is on the order of 1 percent of the cost of electricity. Likely new technologies for removing carbon from flue gases are also likely to be much less costly. For example, the lowest-cost option represented in Figure 5 involves the construction of new integrated gas combined cycle plants that result in control costs about 40 percent lower than retrofitting existing pulverized coal plants.

Second, it is clear that in order for significant progress to be made in reducing U.S. greenhouse gas emissions, some form of mandatory emissions limits or tax on greenhouse gas emissions will be required, just as in every other area of environmental regulation where substantial costs of emissions reductions must be borne. The existing policy based on voluntary reductions has resulted in a very low price for carbon storage (less than \$5 per metric ton of CO<sub>2</sub>, or less than about \$18 per MgC). At this price, only an inconsequential amount of carbon will be sequestered. It is clear from past experience that uniform emissions regulations on power plants and other sources of emissions are highly inefficient and should not be used. Rather, some form of incentive mechanism should be used, either a tax on carbon or a cap-and-trade system. The pros and cons of these two approaches is currently being debated among academics and the policy community (Washington Post, 2007). Proponents of an emissions cap argue that a definite limit on emissions is achieved, whereas proponents of a tax argue that it is substantially lower cost to implement, and can achieve the same emissions target as a cap by adjusting the tax rate.

Third, it is clear that a combination of terrestrial and geologic sequestration options should be pursued as a matter of public policy. Further research and information provision are needed on a number of fronts. In the terrestrial area, major technological advances are not needed, but land managers need better information about the potential benefits and costs of participating in carbon sequestration contracts. Also, because terrestrial sequestration involves a large number of relatively small-scale economic entities that each sequester a relatively small amount of carbon, market institutions need to be developed to pull small land holdings together into larger marketable carbon storage contracts. Moreover, it is clear from experience thus far with terrestrial sequestration projects that participation will be significantly affected by “transaction costs”, including costs of designing and implementing contracts and costs of monitoring contract compliance. Therefore, efforts to provide low-cost information and both technological and institutional means of reducing transaction costs are likely to be extremely important.

In the geologic area, it is clear that there is a need for major new investments in publicly-funded research in both technology and institutions and in regulatory aspects of the system. Many of these challenges are outlined in Ansolabere et al (2007). Their recommendation for making a substantial investment in pilot projects to test technologies at commercial scale should be implemented immediately. In addition, better information on potential costs, in power plant retrofitting, in new designs, and in the regulatory and risk management aspects of geologic sequestration, are urgently needed so that geologic sequestration can move, safely and economically, from testing to commercial implementation as rapidly as possible.

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