Understanding Sequestration as a Means of Carbon Management

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In understanding carbon management options, it is helpful to start with a simple mass balance on anthropogenic carbon emissions to the atmosphere:

$$IN - OUT = ACC \qquad \textbf{(1)}$$

where ACC stands for accumulation. According to the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 1996), for the period of 1980-1989, the values of the terms in the above equation were:

IN = 7.1 GtC[1]/yr
OUT = 3.8 GtC/yr
ACC = 3.3 GtC/yr

The IN term is made up of emissions from fossil fuel combustion and cement production (5.5 GtC/yr) and changes in land-use, commonly referred to as "deforestation" (1.6 GtC/yr). By 1994, the fossil fuel/cement emissions had risen to 6.1 GtC/yr.

The OUT term accounts for uptake by the oceans and the terrestrial biosphere. While the numbers contain quite a bit of uncertainty, it is thought that the ocean accounts for a little more than half of this term.

The ACC term is what stays in the atmosphere and gives rise to concerns about climate change. According to the Framework Convention on Climate Change (FCCC), which has been ratified by the US, "the ultimate objective ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Currently, there is no consensus concerning the level at which stabilization must be achieved, but to achieve stabilization, ACC must be driven to zero.

To make ACC = 0 in Equation (1), we must either decrease IN or increase OUT. To better understand the IN term, we can represent the biggest part, emissions from fossil fuels (CO2), as follows:

$$CO2 = POP x \frac{GDP}{POP} x \frac{BTU}{GDP} x \frac{CO2}{BTU} \qquad \textbf{(2)}$$

where POP is population, GDP/POP is per capita Gross Domestic Product and is a measure of *standard of living*, BTU/GDP is energy consumption per unit of GDP and is a measure of *energy intensity*, and CO2/BTU is the amount of CO2 emitted per unit of energy consumed and is a measure of *carbon intensity*.

We can decrease IN by decreasing any of the four terms in equation (2). Presently, controlling the population term is not politically viable. Also, most people want the standard of living term to increase, not decrease. Therefore, this leaves the options of decreasing the energy intensity (i.e., increasing the efficiency of energy conversion and end-use processes) or decreasing the carbon intensity (i.e., switching to fuels with lower or no carbon content). To date, this is where most carbon management strategies, such as the US Climate Change Action Plan, have focused. One reason for this focus is that energy efficiency and fuel mix are of interest for reasons other than climate change and, therefore, they have been studied extensively in the past. As a result, they

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[1] GtC = billion metric tonnes of carbon

have developed constituencies advocating their use. A quantitative analysis of Equation 2 (see Appendix) shows that driving ACC to zero using just the IN term will be extremely difficult.

While many of the carbon management technologies associated with the IN term had research programs and advocates prior to concerns about climate change, the story is very different with the OUT term. These technologies associated with the OUT term are labeled carbon sequestration. They include enhancing natural sinks like the ocean or the terrestrial biosphere to absorb more CO_2, as well as capturing CO_2 at its source and injecting it into geological formations or into the deep ocean and/or finding ways for its reuse. It is becoming increasingly clear that carbon sequestration can play a major role in helping achieve the goals of the FCCC in a cost-effective manner. However, research into this topic lags well behind energy efficiency and non-fossil energy solutions primarily because historically there has been no large research program into carbon sequestration. Only because of climate change has sequestration become of interest. As a result, its research community and advocates are still a small group.

Why should we do research into carbon sequestration technologies? Here are four reasons:

- There are only a limited number of broad strategies to reduce greenhouse gas emissions. To control greenhouse gas emissions effectively and efficiently (i.e., for least cost), we must explore all options fully.
- With continued research, carbon sequestration technologies have the potential to provide cost-effective greenhouse gas mitigation.
- Carbon sequestration technologies are the only option that can provide long-term greenhouse gas mitigation and still allow for continued large-scale use of our existing fossil infrastructure and our abundant fossil energy resources.
- Carbon sequestration provides an alternate option to completely relying on renewable and nuclear energy.

Carbon sequestration is happening today. As part of the response to the FCCC, several utilities from around the world have started forestation projects. In Norway, the government has imposed a carbon tax of about $50 per tonne of CO_2 (almost $200 per tonne carbon) on some sectors of the economy. As a result, Statoil is sequestering one million tonnes of CO_2 per year in a geological formation 1000 m below the North Sea. The CO_2 is a byproduct of their gas processing operations at their Sleipner West field (see Figure 1). Even more ambitious sequestration projects are now being planned in Norway. This positive role for sequestration that is being demonstrated in Norway is examined more deeply in a White Paper on sequestration commissioned by DOE (Herzog *et al.*, 1997).

In summary, the build-up of carbon in the atmosphere depends on two terms, what we put in and what is taken out. Our traditional research activities have led us to focus on the IN side of this equation. However, we should not ignore the OUT side. To effectively solve the problem, we need to understand what role carbon sequestration can play in addressing climate change concerns. Therefore, as part of our national response to the FCCC, we need to build a carbon sequestration research program of sufficient size to supply the answers we need.

References:

Herzog, H.J., E.M. Drake, and E. Adams, *CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change - A White Paper,* DOE Order No. DE-AF22-96PC01257 (1997). Available over the Internet at <http://web.mit.edu/energylab/www/>.

IPCC, *Climate Change 1995 The Science of Climate Change* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, JT Houghton, LG Meira Filho, BA Callander, N Harris, A Kattenberg and K Maskell, Eds., Cambridge University Press, Cambridge, England (1996).

Appendix: Quantitative Analysis of Carbon Emissions from Fossil Fuel Combustion[2]

Carbon dioxide emissions for a given geographic region can be expressed as the product of four distinct variables as follows:

$$E = A \times B \times C \times D \qquad \textbf{(3)}$$

where E = Total CO_2 emissions
A = Population
B = GDP per capita, which is a measure of **standard of living.**
C = Energy consumed per unit of GDP, which is a measure of **energy intensity.** This number reflects energy conversion and end-efficiency, as well as sectorial make-up.
D = Mass of CO_2 emitted per unit of energy consumption, which is a measure of **carbon intensity**. This number is indicative of the fuel mix.

Differentiating the above equation yields:

$$\frac{dE}{E} = \frac{dA}{A} + \frac{dB}{B} + \frac{dC}{C} + \frac{dD}{D} \qquad \textbf{(4)}$$

Note that the quantity dX/X represents the percentage change in X. In other words, the percentage change in CO_2 emissions is simply the sum of the percentage change of the four components: population, standard of living, energy intensity, and carbon intensity.

Table 1 presents the average annual changes in U.S. CO_2 emissions from fossil energy combustion for several time periods. The changes in each of the four components is also shown. Figures 2-6 show their actual values from 1973-1997. Points of interest include:

- U.S. population has increased at a very steady rate of about 1% per year.
- While energy intensity has decreased almost 2% per year since 1973, this number is misleading. During the "oil shock" period of 1973-1986, energy intensity decreased almost 3% per year, in part due to the price signal. Since the return of the lower prices in 1986, the improvement has been a very modest 0.6% per year.
- Carbon intensity has shown only a modest decrease. It may actually increase under a business-as-usual scenario where nuclear plants are decommissioned.
- Major reasons for the large increase in CO_2 emissions since 1990 have been the strong economy and low energy prices, conditions most people strongly desire. This highlights the difficulty of controlling CO_2 emissions strictly by focusing of the "IN" term.

A world view for the years 1980-1993 are shown in Table 2. Some observations:

- the collapse of the economies in Eastern Europe and the former Soviet Union allowed them to reduce CO_2 emissions by 1% per year. We do not want to follow this path.

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[2] This analysis was conducted using data from the Energy Information Agency of the U.S. Department of Energy.

- The largest percentage growth in CO_2 emissions occurred in China, India, and East Asia, fueled by strong economic growth. The Asian economic slowdown will slow this growth, at least temporarily.

- China's growth was moderated by its large decrease in energy intensity. The reasons are not well understood and are the subject of current research, including by several of my colleagues at MIT.

- Europe has decreased their CO_2 emissions by about 0.5% per year, primarily through fuel switching. This was driven by abundant gas supplies from the North Sea and Russia, ending coal subsidies, and nuclear power in countries like France.

Table 1. Average Annual Percent Changes of Carbon Dioxide Emissions Variables for the US

Time Period	POP	GDP/POP	BTU/GDP	CO2/BTU	CO2
since 1973	+0.97	+1.67	-1.81	-0.17	+0.65
last 10 years	+1.02	+1.17	-0.70	-0.26	+1.21
since 1990	+1.01	+1.40	-0.66	-0.15	+1.60
last 5 years	+0.96	+1.80	-0.72	-0.14	+1.91

Table 2. Average Annual Percent Change Carbon Dioxide Emissions Variables for 1980-1993

REGION	POP	GDP/POP	BTU/GDP	CO2/BTU	CO2
OECD Europe	+0.5	+1.4	-1.0	-1.4	-0.5
Japan	+0.5	+3.0	-1.5	-0.7	+1.4
EE and FSU	+0.6	-1.5	+0.8	-0.9	-0.9
East Asia	+1.7	+4.9	+0.3	-0.5	+6.5
China	+1.4	+7.8	-4.4	0.0	+4.7
India	+2.0	+3.0	+1.1	+0.2	+6.3
Africa	+2.8	-1.7	+2.0	0.0	+3.2
OECD	+0.7	+1.8	-1.4	-0.7	+0.4
The World	+1.7	+0.8	-0.9	-0.4	+1.2

Figure 1: The Sleipner CO_2 - Injection project.

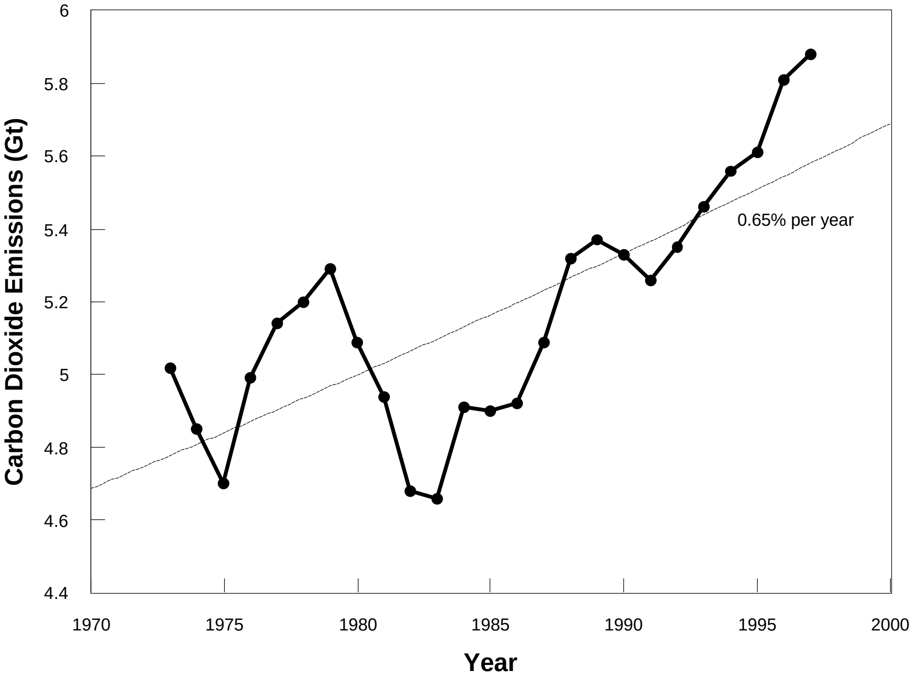

Figure 2: US carbon dioxide emissions from fossil fuel combustion increased an average of 0.65% per year from 1973 to 1997.

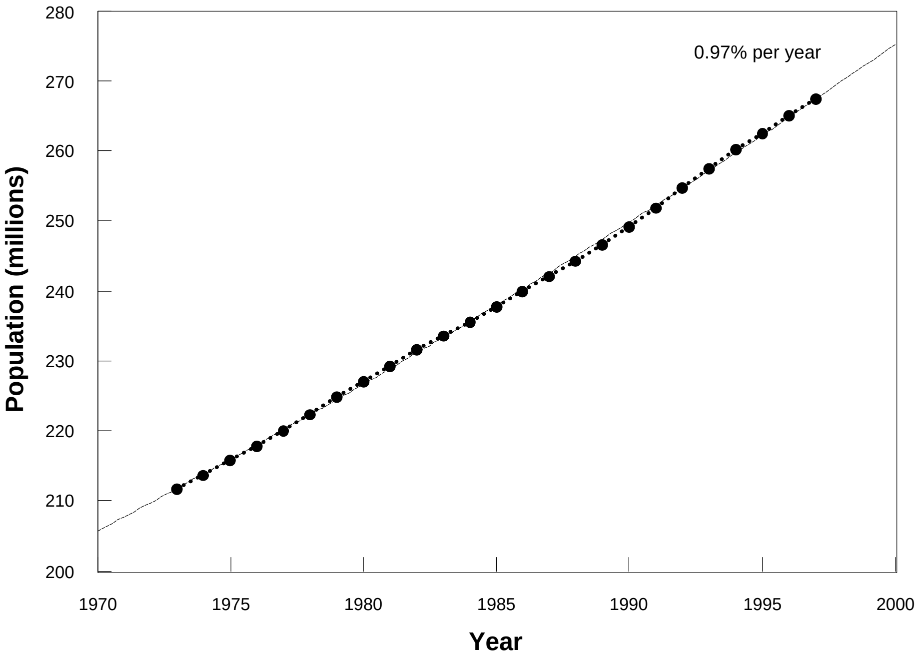

Figure 3: The US population grew at an average rate of just under 1% per year from 1973 to 1997.

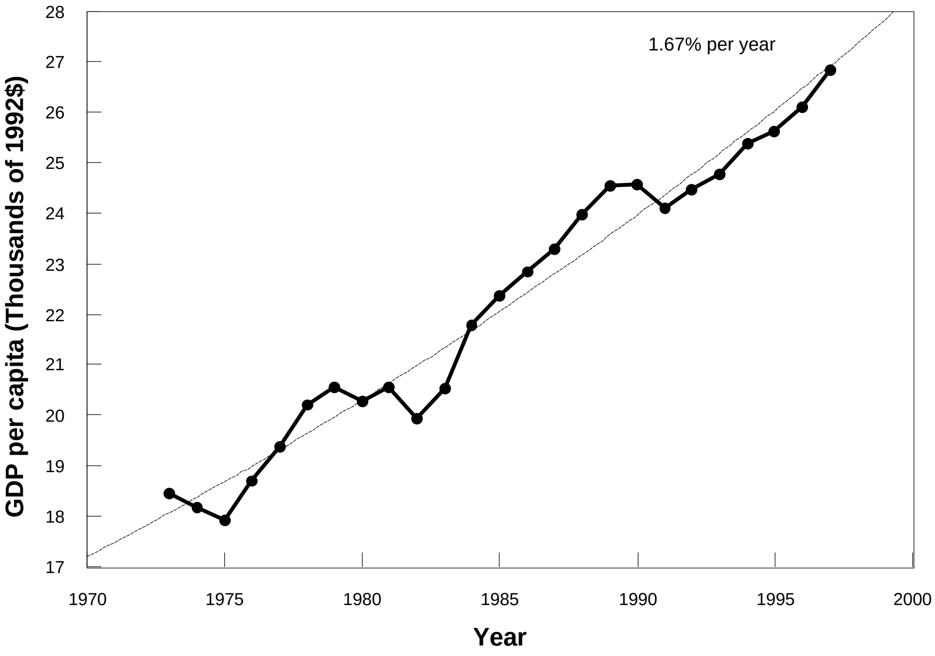

Figure 4: The US per capita GDP grew at an annual rate of 1.67% per year from 1973-1997.

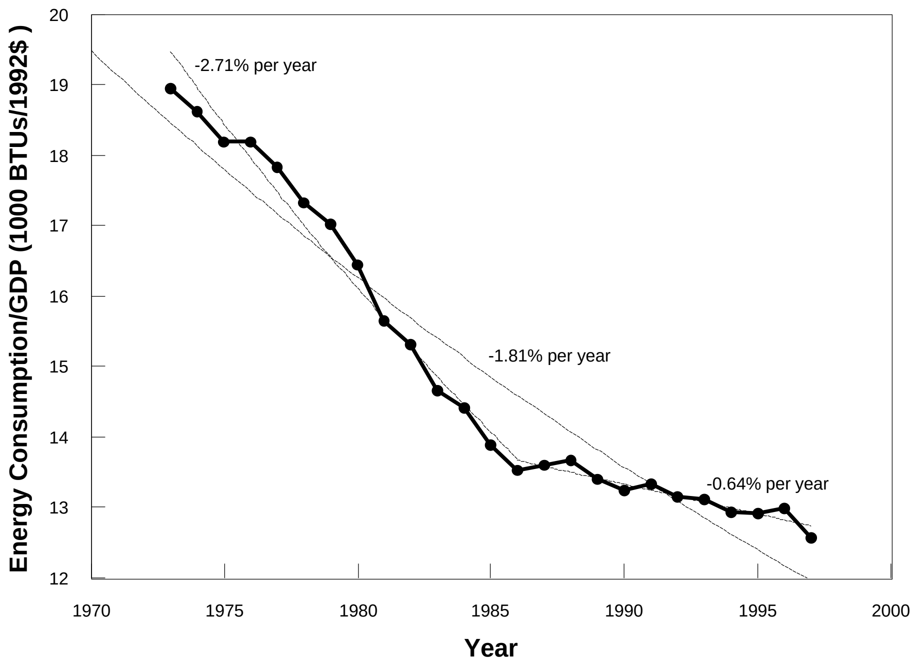

Figure 5: The US energy intensity, as measured by energy consumed per unit of GDP, decreased an average of 1.81% per year from 1973-1997. However, the rate of decrease was much more modest since energy prices dropped in the mid-1980's.

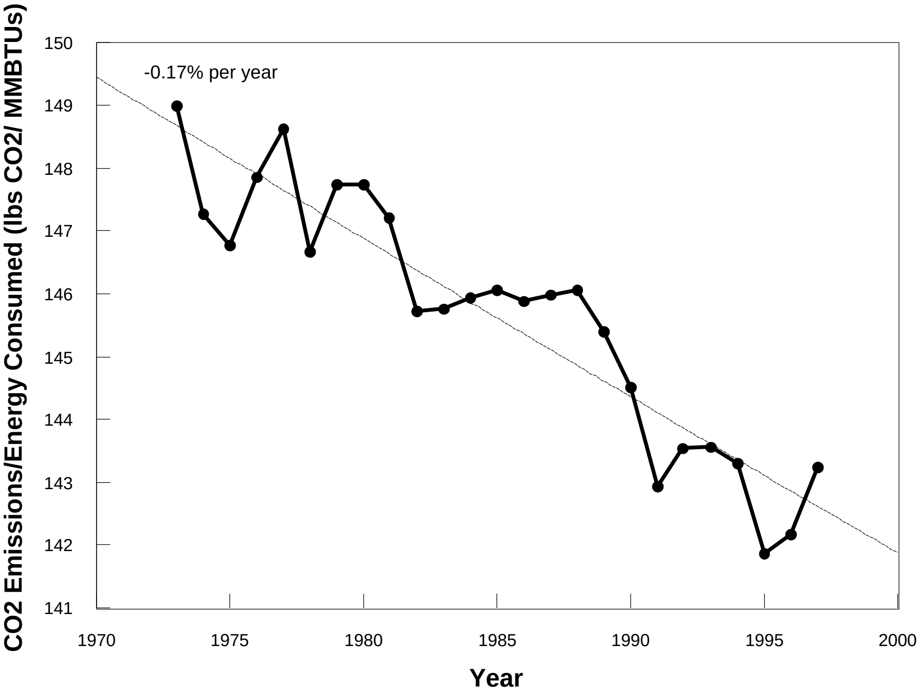

Figure 6: The carbon intensity of the US fuel mix decreased at a rate of 0.17% per year from 1973-1997.