International Emission Trading and the Cost of Greenhouse Gas Emissions Mitigation and Sequestration

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Abstract

The deployment of carbon capture and sequestration (CC&S) technologies is greatly affected by the marginal cost of controlling carbon emissions (also the value of carbon, when emissions permits are traded). Both the severity and timing of emissions limitations and the degree to which emissions limitation obligations can be traded will affect the value of carbon and thereby the timing and magnitude of CC&S technology deployment. Emissions limits that are more stringent in the near term imply higher near-term carbon values and therefore encourage the local development and deployment of CC&S technologies.

Trade in emissions obligations lowers the cost of meeting any regional or global emissions limit and so affects the rate of penetration of CC&S technologies. Trade lowers the marginal value of carbon in high cost regions and raises it in low cost regions. The net impact on the penetration of CC&S technologies depends on whether their increased use in low-cost regions exceeds the reduced use in high-cost regions.

In the long term, CC&S technologies must deal with the issue of permanence. It is not the removal of the carbon from the waste-gas stream that prevents emissions; it is the sequestration of that carbon. If reservoirs are not permanent, then the emissions are merely displaced in time. Sequestration options vary in their permanence from carbon

removed in the form of a solid such as calcium carbonate to carbon that is merely mixed in the general ocean. For non-solid carbon disposal the issue of monitoring arises and with it the potential for discounting of the sequestered carbon.

In this paper we examine the issues outlined above and present quantitative estimates for the impacts of trade in emissions limitation obligations on the timing, magnitude, and geographic distribution of CC&S technologies.

Introduction

Carbon capture and sequestration (CC&S) technologies remove carbon from emissions streams or the atmosphere and sequester it in some form for a relatively long time—decades to millennia. The deployment of CC&S technologies to meet an emissions limit is greatly affected by the value of carbon. The severity and timing of the emissions limit and the degree to which emissions limitation obligations can be traded all affect the value of carbon and thereby the timing and magnitude of CC&S deployment. Emissions limits that are more stringent in the near term imply higher near-term carbon values and therefore encourage the local development and deployment of CC&S technologies.

Trade in emissions obligations lowers the cost of meeting any regional or global emissions limit and so affects the rate of penetration of CC&S technologies. Trade lowers the marginal value of carbon in high-cost regions and raises it in low-cost regions (Edmonds et al. 1999). The net impact on the penetration of CC&S technologies depends on whether their increased use in low-cost regions exceeds the reduced use in high-cost regions.

In the long term, CC&S technologies must deal with the issue of permanence. It is not the removal of the carbon from the waste-gas stream that prevents emissions; it is the sequestration of that carbon. If reservoirs are not permanent, the emissions are merely displaced in time. Sequestration options vary in their permanence from carbon removed in the form of a solid such as calcium carbonate to carbon that is merely mixed in the general ocean. For non-solid carbon disposal the issue of monitoring arises and with it the potential for discounting of the sequestered carbon.

Objective

In this paper we examine the issues outlined above and present quantitative estimates for the impacts of trade in emissions limitation obligations on the timing, magnitude, and geographic distribution of CC&S technologies. We use an updated version of PNNL's MiniCAM model (Dooley et al. 1999; Edmonds et al. 1997; and Edmonds et al. 1996), which is an integrated assessment model of global change with a focus on the world's energy and agriculture systems. We consider two broad categories of CC&S actions—CC&S technologies and soil and biological sequestration. Carbon capture is explicitly represented in the model at key fuel transformation nodes. Capture and sequestration technologies are modeled generically in terms of their cost and performance characteristics. CC&S technologies are adopted if the economics are favorable.

Biological sequestration in forests and agricultural soils is not explicitly modeled. Instead, an exogenous scenario of carbon sequestration in biological sinks is specified. The amount of carbon sequestered in this way is added to the global emissions target and the corresponding scenario costs are added to the emissions compliance costs determined by the model.

Approach

Theoretical Issues

Carbon capture and sequestration technologies can be thought of as an alternative mitigation technology for preventing the buildup of carbon in the atmosphere. As with other mitigation technologies, CC&S technologies have assumed schedules of future cost and performance. These costs and performance schedules are expected to differ by region because each region will have unique features of energy technology and options for capture systems, transport and disposal, and storage. If a future regulatory regime allows international trade in emission permits, then permits will compete on a cost basis with both domestic emission reduction and domestic carbon CC&S as regions attempt to meet their mitigation obligations.

To see the issues involved, imagine a country facing the situation diagrammed in Figure 1. The country has a domestic schedule of carbon mitigation options that increase in marginal cost as more carbon is controlled. If the country had an obligation to reduce its carbon emissions by, say, 650 million metric tons per year and it did this entirely via emissions reduction, Figure 1 shows that the marginal abatement cost (cost of the last, or 650 millionth ton removed) would be about $300/ton. Its total abatement cost would be the area under the curve, which is $69 billion per year. If the country also could remove carbon from power plant emissions or from the atmosphere according the CC&S cost schedule, the *combined* options could be far less costly. In Figure 1, the marginal cost of removing 650 million metric tons would be about $155/ton and the total cost about $35 billion per year. At $155/ton, the cost curves in Figure 1 show that about 465 million metric tons would come from emissions reduction and about 185 million metric tons from CC&S.

What effect would trade in carbon permits have on the domestic emission situation? Imagine a situation in which there is a large amount of inexpensive emissions control available internationally and an active market for emissions permits. Suppose that the market-clearing price is $50/ton, as many researchers believe it might be with world-wide trading (Edmonds et. al. 1999). Then, domestic emissions reduction and CC&S would be used to meet the county's 650 million ton abatement obligation only to the extent that such mitigation cost less than $50/ton. Figure 1 shows this happening at about 350 million metric tons, 250 million from emissions reduction and 100 million from CC&S. The other 300 million metric tons would be met by the purchase of emissions permits at $50/ton. The marginal cost would be $50 per ton and the total cost would be $21.5 billion ($6.5 billion domestic abatement plus $15 billion in permits).

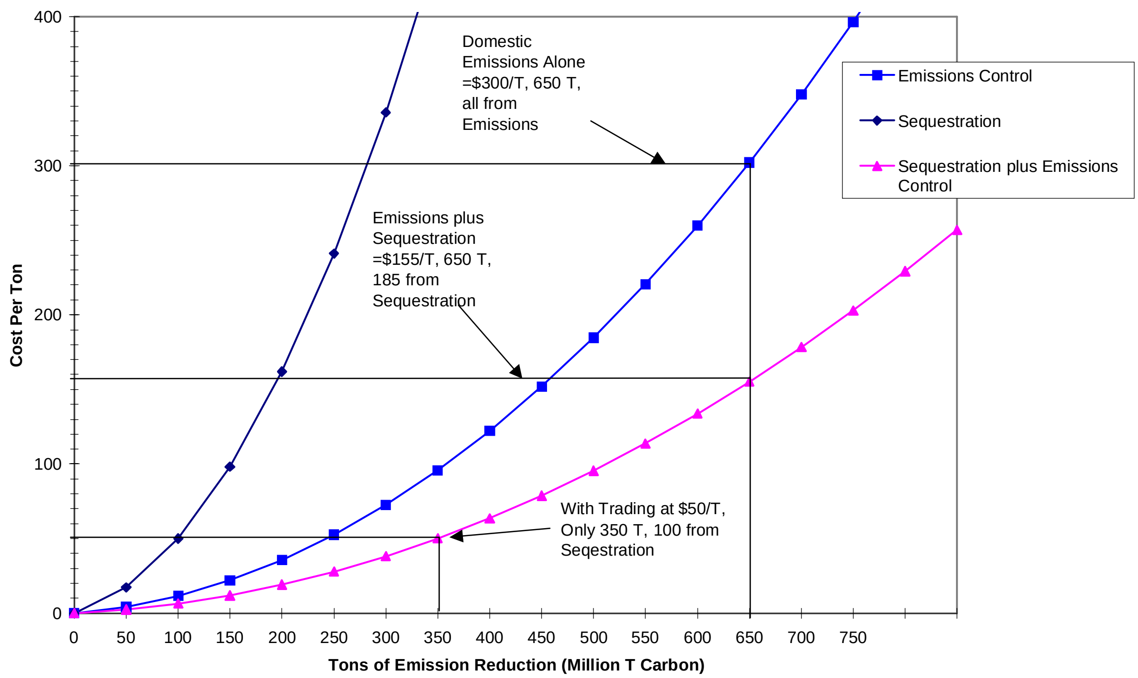

Figure 1. Comparative Costs of Carbon Mitigation through Emissions Control, CC&S, and Emissions Trading

The country in Figure 1 is a high-cost region -- its marginal control cost is $155 per ton compared to the international marginal cost of $50 per ton. One of the consequences of trade is to reduce domestic mitigation in high-cost regions. Domestic emission reduction falls from 465 to 250 million metric tons and use of CC&S technologies falls from 185 to 100 million metric tons. Since the global emissions limit is unchanged, emission reductions and use of CC&S technologies in low-cost regions must rise by 300 million metric tons, the amount of the permits sold. If to generate the 300 million ton additional reduction, the use of CC&S technologies in low-cost regions increases by more than 85 million metric tons, then global penetration of CC&S technologies increases as a result of trade. On the other hand, if more than 215 million metric tons of the additional reduction comes from extra emission reductions, the global penetration of CC&S technologies falls due to trade.

It is not the removal of the carbon from the waste-gas stream that prevents emissions; it is the sequestration of that carbon. If reservoirs are not permanent, then they represent a future net source of emissions. Given that the long-term (centuries to millennia) concentration of CO_2 in the atmosphere depends on cumulative emissions of carbon, temporary storage of carbon is inferior to permanent storage. Carbon mitigation costs could rise over time if emission targets must be increased in the future to make up for the carbon "leaking" back into the atmosphere from temporary sequestration options.

Model and Assumptions

To analyze the issues identified above, we use PNNL's MiniCAM model, Version 14C. MiniCAM is an integrated assessment model of global change with a focus on the world's energy and agriculture systems. Version 14C is an updated version of the MiniCAM model described in Dooley et al. (1999), Edmonds et al (1998), and Edmonds et al. (1996). MiniCAM 14C differs from previous versions in that it incorporates carbon capture and sequestration technology options, a hydrogen fuel option, and a global market for biomass energy.

Carbon capture is explicitly represented in the model at key fuel transformation nodes. Carbon capture and sequestration technologies are modeled generically in terms of their cost and performance characteristics. Carbon is captured and sequestered if economics are favorable or if policy mandates it. Carbon sequestration in biological sinks such as forests and in soils is not explicitly handled by MiniCAM. Instead, an exogenous scenario of carbon capture and sequestration in soils and biological sinks is specified. The amount of carbon sequestered in this way is added to the global carbon target and the corresponding costs are determined. The costs are added to those estimated by the model to meet the remainder of the carbon target.

MiniCAM 14C's reference scenario is intended to reflect in large measure a continuation of many present trends. We assume that global population will eventually stabilize at approximately eleven billion people. We assume that regions that are rapidly developing will continue to close the per capita income gap with developed nations and approach parity with the presently developed world over the course of the next century. Those presently growing less rapidly are assumed to begin the process of more rapid development some time during the next century. The technical efficiency and cost performance of existing energy technologies is assumed to continue improving over time. For example, fossil fuel power plants are assumed to reach an efficiency level of 66 percent by 2050 and the cost of solar electricity is assumed to reach 10 cents/kWh in 2035, and to decrease by 1 percent per year thereafter. We also assume that end-use energy intensities decline in all regions.

Modeling Carbon Capture And Sequestration Technologies
To model the cost and performance of the carbon capture and sequestration technologies within MiniCAM, we decompose these costs into three categories and make assumptions about how the costs change and the technologies will perform over time. Table 1 illustrates the set of sequestration opportunities in geological formations and the ocean.

The Parasitic Energy Costs of Capturing CO_2: The capture of CO_2 from the emissions stream of a plant requires energy. We assume that the efficiency of carbon capture will increase with time, i.e., new and improved technologies and processes will come on-line that reduce the energy penalty associated with powering the capture systems. Herzog et. al. (1997) state that the eventual integration of these systems into the overall design of new fossil fueled power plants—such as integrated gasification combined cycle (IGCC) power plants—holds forth the promise of reducing the cost of CO_2 capture significantly. Further, recent research indicates that targeted basic science programs could lead to advancements that over time would improve the performance and reduce the costs of these systems (Dooley and Edmonds 1997). We assume that the phasing in of these more efficient capture technologies will occur gradually and will be completed 50 years after the initiation of carbon capture.

Table 1. Opportunities for Carbon Sequestration.

Carbon Storage Reservoir	Range (Billion Metric Tons of Carbon)
Deep Ocean	1,391 to 27,000
Deep Saline Reservoirs	87 to 2,727
Depleted Gas Reservoirs	136 to 300
Depleted Oil Reservoirs	41 to 191
Unminable Coal	> 20

Source: Herzog et al. (1997), Freund and Ormerod (1997).

Additional Capital Costs for the Carbon Capture System: We base our assumptions for the additional capital investment needed for the CO_2 capture system largely on the work of Gottlicher and Pruschek (1997) and their comprehensive survey of over 300 studies of CO_2 removal systems from fossil-fueled power plants. Gottlicher and Pruschek's estimates of the performance of CO_2 removal systems are based on the "present status of the technology," and therefore we adopt the same assumption about costs decreasing over time. We adopt the mid-range cost reported by Gottlicher and Pruschek (1997) from their survey.

CO_2 Transport Costs: For the foreseeable future, the vast majority of research relating to disposal applications is likely to be focused on understanding and mitigating environmental concerns that arise from disposal rather than at reducing the cost of disposal (Freund and Ormerod, 1997). Freund and Ormerod (1997) cite estimates for transport and disposal costs that range from \$4.7/metric ton of CO_2 to \$21/metric ton of CO_2, depending upon whether the sequestration takes place in a nearby depleted oil and gas well or a deep sea trench that is located some distance from an on-shore fossil-fueled power plant. In the absence of research that pairs current and future power plant sites with disposal sites on a global basis, we will assume an intermediate value of \$15/metric ton CO_2, which works out to \$55/metric ton C for all transport and disposal costs and hold this cost constant throughout the time period under study.

CO_2 will also need to be captured from fuel conversion facilities such as plants for the conversion of coal to synthetic liquids and gases. Herzog et al. (1997) state that the cost of CO_2 capture from refineries will be comparable to or greater than the cost of capture from fossil-fueled power plants. Therefore, we assume that all conversion facilities and refineries will have performance characteristics similar to those for coal-fired plants. We summarize our assumptions for carbon capture and sequestration in Table 2. The figures in Table 2 are not representative of any given capture and sequestration system configuration but rather are meant to be averages for the entire suite of carbon capture and sequestration technologies and systems that could be deployed in any number of possible combinations.

Table 2. Assumed Cost and Performance of Carbon Capture and Sequestration

Cost Element	Oil & Coal	Gas
Energy Penalty for Carbon Capture [a]	20% declining to 13%	20% declining to 13%
Additional Investment Costs for Capture System [b]	33% declining to 23%	46% declining to 31%
Transport and Disposal Cost [c]	\$55/metric ton of C	\$55/metric ton of C
Efficiency of Capture [b]	90%	90%

Sources: (a) Herzog, et. al. 1997, (b) Gottlicher and Pruschek, 1997, (c) Freund and Ormerod, 1997

Capture and Sequestration in Forests, Soils and Land Management Sinks: The generic CC&S technology does not cover sequestration of carbon by increasing the uptake of carbon in soils and terrestrial biomass.

Much effort is currently being expended in the research community to estimate the amounts and costs of CO_2 capture and sequestration that may be possible by activities such as afforestation, reforestation, changes in agricultural practices, and other activities to enhance biological carbon sinks. The recent analyses include Watson et al. (2000), Kremen et al. (2000), Manne and Richels (1999), MacCracken et al. (1999), Reilly et al. (2000), Nilsson and Schopfhauser (1995), Noble and Scholes (2001), Adams et al.(1999), Schwarze (1999), and Woerdman and van der Gaast (2000). Much of this work is focused on the near-term availability and cost of sequestration in soils and forests to meet the greenhouse gas mitigation obligations of countries under the Kyoto Protocol and depends heavily on the accounting conventions used.

Our objective here is longer-term, more general, and in terms of total mitigation, more ambitious. The opportunities for soil and biological sequestration of carbon start slowly (200 to 400 million metric tons per year) because of phase-in costs, rise to a peak rate of 400 to 800 million metric tons per year during the middle of the century, and then decline as opportunities for soil sequestration are saturated (Rosenberg et al. 1998). Noble and Scholes (2001) estimate that worldwide, carbon uptake activities allowable under Article 3.4 of the Kyoto protocol might be as high as 2.2 billion metric tons of carbon per year by 2040. Other sources show different comparisons and different values, but this is probably near the upper limit of additional sequestration that might be expected before saturation of the capability.

To get annual sequestration of 2.2 billion metric tons requires that all of the following activities be implemented to the fullest extent feasible:

- Improved land management
- reduced tillage and erosion control on croplands
- enhanced forest regeneration and fertilization
- better herd and fire management on rangelands
- agroforests
- wood product management on urban lands
- deliberate land use changes
- deforested land to agroforest instead of pasture or crops
- restore severely degrade land
- cropland to grassland.

There is a high degree of overlap between these activities and activities accounted for elsewhere in the MiniCAM model, since it is assumed, for example, that all forests are managed and that cropland will be allocated as appropriate between biomass and crops. While the Noble and Scholes estimate of 2.2 billion metric tons per year is high because of such double counting of land use, it provides a useful upper limit for soil and biological sequestration potential. The assumptions on biological and soil sequestration vary by case, as discussed below.

The literature also reports a variety of costs for biological sequestration activities, ranging from \$0/ton for some easier, near-term activities to as high as \$450/ton. Most estimates, however, range from \$0/ton at the low end to \$50/ton at the high end. We use a marginal cost of \$0 for biological sequestration to take maximum advantage of this type of sequestration. In a later section, the paper allows for the natural emission of carbon from these sequestered pools.

Scenarios

In this paper we deal with a base case of "business as usual" and three cases in which varying degrees of trading are utilized to achieve a carbon mitigation path that results in a long-term atmospheric concentration of 550 ppm. The business as usual case, Intergovernmental Panel on Climate Change (IPCC) Case IS92a, and the 550 target mitigation scenario, WRE550 (named for its authors, Wigley, Richels, and Edmonds, and the atmospheric carbon target level of 550 ppm), have both been discussed extensively elsewhere (e.g., Wigley et al. 1996). It is important to note *inter alia* a point that does not appear in most analyses of the Kyoto Protocol, which are relatively short-run in orientation. The picture of what is possible changes significantly after 2020 because of the rapid rate of growth in the emissions of non-Annex I countries. Given the population and economic growth assumptions that underlie business-as-usual cases such as IS92a, achieving a stable atmosphere at 550 ppm by the end of the 21st century requires significant carbon control by non-Annex I countries. Annex I countries cannot achieve atmospheric stabilization at 550 ppm by themselves. For our trading cases, therefore, we consider the following:

- *No Trade—Each nation (region) undertakes its own emissions reduction and sequestration independently. Only the Annex I countries specified in the Rio Treaty are initially required to undertake emissions reductions. There are many possible ways in which the WRE550 responsibilities could be specified. For this paper, we assume that individual country Annex I[1] responsibilities are equal to those in the WRE550 case until 2020. Non-Annex I countries undertake no emission reductions until their combined emissions reach the same total as those of the Annex I countries (half the world total). This happens about 2020. Each country is then allocated an amount of emissions equivalent to its year 2020 share of the world total for each year in the remainder of the forecast period. This means that once the WRE550 case requires worldwide reductions (in the year 2050), reductions are proportional in each country.*

- *Annex I Trading—Responsibilities are the same as in the no-trade case. The United States, Japan, Western Europe, Canada, Australia-New Zealand, Eastern Europe, and the Former Soviet Union (FSU) create a trading block to trade carbon emissions permits (and in some cases, carbon sequestration credits). Non-Annex I countries retain individual country responsibilities.*

- *World Trading—All countries in the world trade emissions permits and sequestration credits. The same responsibility issues apply as in the previous two cases.*

Analysis

Base Case-Business as Usual

For the base case we use the IPCC IS92a emissions case, which assumes considerable technological improvement and implementation of energy-conservation technology over the next century, but no explicit policy to reduce carbon emissions. While this case does not reflect the latest thinking of the climate community, it has the advantage that many articles have examined its climate implications. In terms of emissions, it is also near the center of the range usually discussed in the literature. Table 3 shows values for some of the key variables for several world regions.

WRE550 - No Trade Case

The WRE550 case begins with business as usual emissions through the early part of the 21st century. By 2020, however, countries have to begin to reduce their carbon emissions from the path they otherwise would have followed, and by 2050 most countries have begun to reduce their emissions in absolute terms. While only Annex I countries control carbon initially, the "soft landing" implied by WRE550 cannot be achieved without very broad international participation in carbon reduction, including the eventual participation of the developing world. Atmospheric carbon continues to rise for a while because it is relatively stable in the atmosphere. Eventually, however, the concentration also declines. Table 4 illustrates the impacts on emissions in the WRE550 No Trade Case.

Table 3. Business as Usual Case: IS92a Case: Population, Emissions by Region, World Atmospheric Concentration. 1990, 2005, 2020, 2050, 2095

Variable and Region	1990	2005	2020	2050	2095
Population (Millions)					
USA	249	275	295	297	294
WEUR	413	433	442	431	425
FSU	317	342	361	383	380
All Annex I	1,257	1,347	1,405	1,424	1,408
China	1,223	1,467	1,657	1,858	1,917
India	845	1,082	1,287	1,604	1,784
All Non-Annex I	4,070	5,338	6,609	8,652	9,817
World Total	5,326	6,685	8,014	10,076	11,225
Emissions (Million Metric Tons of Carbon)					
USA	1,467	1,679	1,968	2,413	2,687
WEUR	1,140	1,374	1,481	1,725	1,980
FSU	1,086	818	1,009	1,325	1,481
All Annex I	4,606	4,851	5,659	6,788	7,993
China	710	1,309	1,768	2,267	3,695
India	158	389	601	537	1,366
All Non-Annex I	1,904	3,444	5,097	6,794	11,420
World Total	6,510	8,296	10,756	13,582	19,413
Global Carbon Concentration (ppm)	354	392	430	512	679

With sequestration options available, the amount of emissions can be higher by the net amount sequestered. In addition, as was shown in Figure 1, the marginal and total costs of emissions control can be lower with CC&S options available. The contribution of CC&S technologies to meeting the emissions limits of the basic WRE550 No Trade Case is shown in Figure 2. The biological and soil sequestration component peaks at about 935 million metric tons per year in 2035, then slowly declines to 175 million metric tons in 2095 as opportunities (mainly) within the Annex I countries are exhausted. At this point we assume that carbon can be captured and permanently sequestered from the sources mentioned earlier.

As can be seen from Figure 2, CC&S makes a substantial contribution. For the Annex I countries, CC&S contributes almost 60% of the reduction effort required in 2020, nearly 30% of the total reduction effort in 2050, and 17% by 2095. In the absence of CC&S technologies, the amount provided from CC&S must be made up by energy conservation, and fuel switching. The marginal and total costs are considerably higher without CC&S, as is illustrated in Table 5.

Table 4. WRE550 No Trade Case: Emissions Reduction and CC&S Contribution by Region, World Atmospheric Concentration. 1990, 2005, 2020, 2050, 2095 (Million Metric Tons of Carbon).

	1990	2005	2020	2050	2095
Emissions Reduction from Business-as-Usual					
USA	-	41	140	631	1,507
WEUR	-	36	107	385	1,093
FSU	-	20	74	413	877
All Annex I	-	123	411	1,678	4,604
China	-	19	29	322	2,407
India	-	9	15	17	984
All Non-Annex I	-	39	215	1,038	3,980
World Total	-	190	670	3,140	12,028
Contribution from Sequestration					
USA	-	-	246	266	388
WEUR	-	-	162	154	275
FSU	-	-	140	164	194
All Annex I	-	-	731	757	1,146
China	-	-	(8)	218	404
India	-	-	73	7	214
All Non-Annex I	-	-	290	615	1,367
World Total	-	-	1,022	1,372	2,513
Global Carbon Concentration (ppm)	354	392	425	480	532

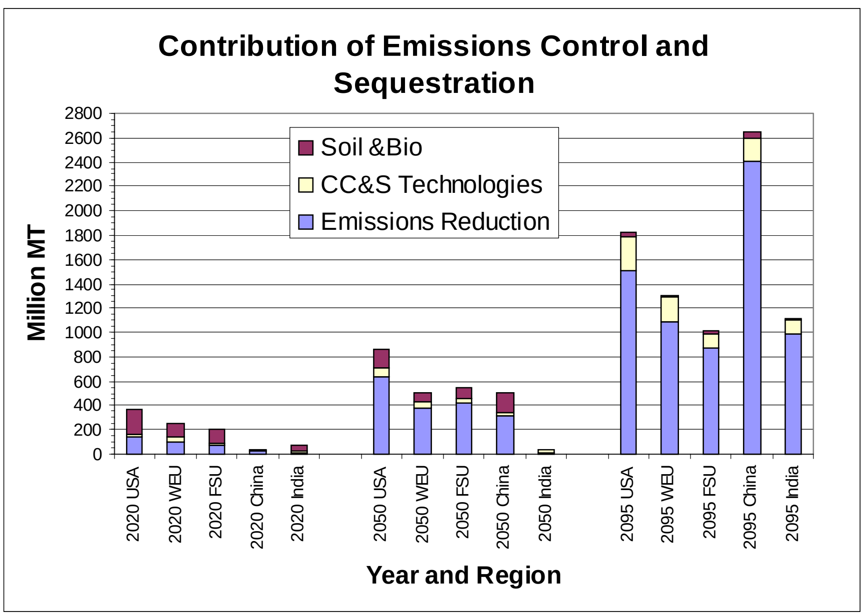

Figure 2. Emissions Reduction, CC&S, and Soil and Biological Sequestration for Selected Regions, WRE550 No Trade Case

In 2020 sequestration accounts for about 60% of the abatement effort, but CC&S reduces total abatement costs by 90% (soil and biological sequestration costs are assumed to be near zero, and they make up most of the early sequestration); in 2050 the figures are 30% of the total effort and 55% reduction in abatement costs; and in 2095 the CC&S technologies represent 18% of the reduction effort yet they reduce abatement costs by 29%. That suggests a rather inelastic abatement cost curve. Through 2050, biological sinks dominate sequestration due to their low costs. About that time their capacity is becoming exhausted and the costs of CC&S technologies become more competitive, so that total CC&S and total sequestration rises. The amount of CC&S is constrained by cost rather than any lack of sequestration opportunities. Available opportunities are three orders of magnitude larger than the amount sequestered (see Table 1).

One of the effects of carbon emission reduction is that fossil fuels become less attractive, and their price falls. This has the effect of depressing the economies of energy-exporting countries. A certain amount of economic activity will migrate from economies where it is expensive to control emissions to countries where it is relatively inexpensive. The presence of the CC&S options takes some of the pressure off of the fossil fuel markets and moderates these "leakage" effects.

Table 5. WRE550 No Trade Case: Marginal Carbon Cost and Total Abatement Cost by Region, with and without Carbon Capture and Sequestration, 2020, 2050, 2095 (Billion 1997 US$)

	2020		2050		2095	
Marginal Carbon Cost	Without Sequestration	With Sequestration	Without Sequestration	With Sequestration	Without Sequestration	With Sequestration
USA	$ 60.46	$ 12.61	$ 140.60	$ 71.40	$ 423.72	$ 317.76
WEUR	$ 64.87	$ 15.42	$ 127.86	$ 63.19	$ 488.69	$ 386.97
FSU	$ 56.57	$ 11.02	$ 156.06	$ 108.36	$ 400.74	$ 308.18
All Annex I	N/A	N/A	N/A	N/A	N/A	N/A
China	$ 0.59	$ 0.59	$ 42.91	$ 22.30	$ 183.15	$ 125.75
India	$ 29.40	$ 0.59	$ 2.85	$ 0.59	$ 440.97	$ 302.12
All Non-Annex I	N/A	N/A	N/A	N/A	N/A	N/A
World	N/A	N/A	N/A	N/A	N/A	N/A
Total Abatement Cost						
USA	$ 9.6	$ 0.7	$ 45.2	$ 18.8	$ 249.2	$ 173.7
WEUR	$ 7.0	$ 0.6	$ 23.8	$ 9.2	$ 219.0	$ 161.8
FSU	$ 5.1	$ 0.3	$ 35.7	$ 18.3	$ 137.2	$ 97.9
All Annex I	$ 28.0	$ 1.9	$ 117.7	$ 50.3	$ 767.8	$ 532.4
China	$ 0.0	$ 0.0	$ 10.0	$ 3.3	$ 163.4	$ 115.9
India	$ 1.1	$ 0.0	$ 0.0	$ 0.0	$ 139.1	$ 88.3
All Non-Annex I	$ 11.3	$ 2.0	$ 96.5	$ 47.7	$ 1,280.3	$ 919.9
World	$ 39.3	$ 3.9	$ 214.2	$ 98.0	$ 2,048.1	$ 1,452.3

Annex I Trading Case

If trading in emission permits is allowed, it opens up the possibility of reducing the marginal costs of emissions abatement, as countries with higher marginal costs of emissions abatement (high-cost controllers) purchase emissions permits from countries with lower marginal costs of abatement (low cost controllers). Significant savings in total abatement costs can be realized from reallocating the actual carbon abatement. The savings are commonly called gains from trade. If trading of emissions permits is allowed, the cost to the high-cost controller is a concept we will call Total Obligation Cost. It is the total cost of domestic emissions abatement, plus the cost of purchasing any permits, minus the value of any emissions permits sold. If CC&S technologies are also added to the mix of options, then Total Obligation Cost equals the total domestic cost of abatement, plus the total cost of domestic carbon capture and sequestration, plus the cost of any purchases of emissions permits or carbon credits, minus the value of permits and credits sold. For high-cost controllers, the presence of trading generally will mean that the region will take advantage of relatively fewer domestic CC&S opportunities. For low-cost controllers, who will be in the business of selling emissions permits and carbon credits for CC&S, the Total Emission Obligation Cost has the same definition, but the net value of permits and credits sold will be positive and will offset domestic abatement and carbon capture costs.

Whether trade in permits reduces the global penetration of CC&S technologies depends on the marginal costs of CC&S relative to emissions reduction in different regions. If most CC&S opportunities are relatively high-cost and are located in high control cost countries, then international trade in emission permits would reduce global reliance on CC&S technologies. If most CC&S opportunities are low-cost and are located in high control cost countries, international trade in emissions permits would have little impact on the use of those technologies. If most CC&S opportunities are located in low control cost countries, trade might expand both the scope of CC&S and the volume of trade in permits.

The basic result appears to be that Annex I trading has minimal impact on the use of CC&S technologies. There are small reductions in the use of CC&S technologies in high control cost regions and small increases in the use of CC&S technologies in low control cost regions. This occurs despite 25% to 40% reductions in marginal control costs in high cost regions. That suggests that CC&S opportunities are concentrated in the lower cost portion of the marginal abatement cost curve, reflecting the impact of soil and biological sequestration.

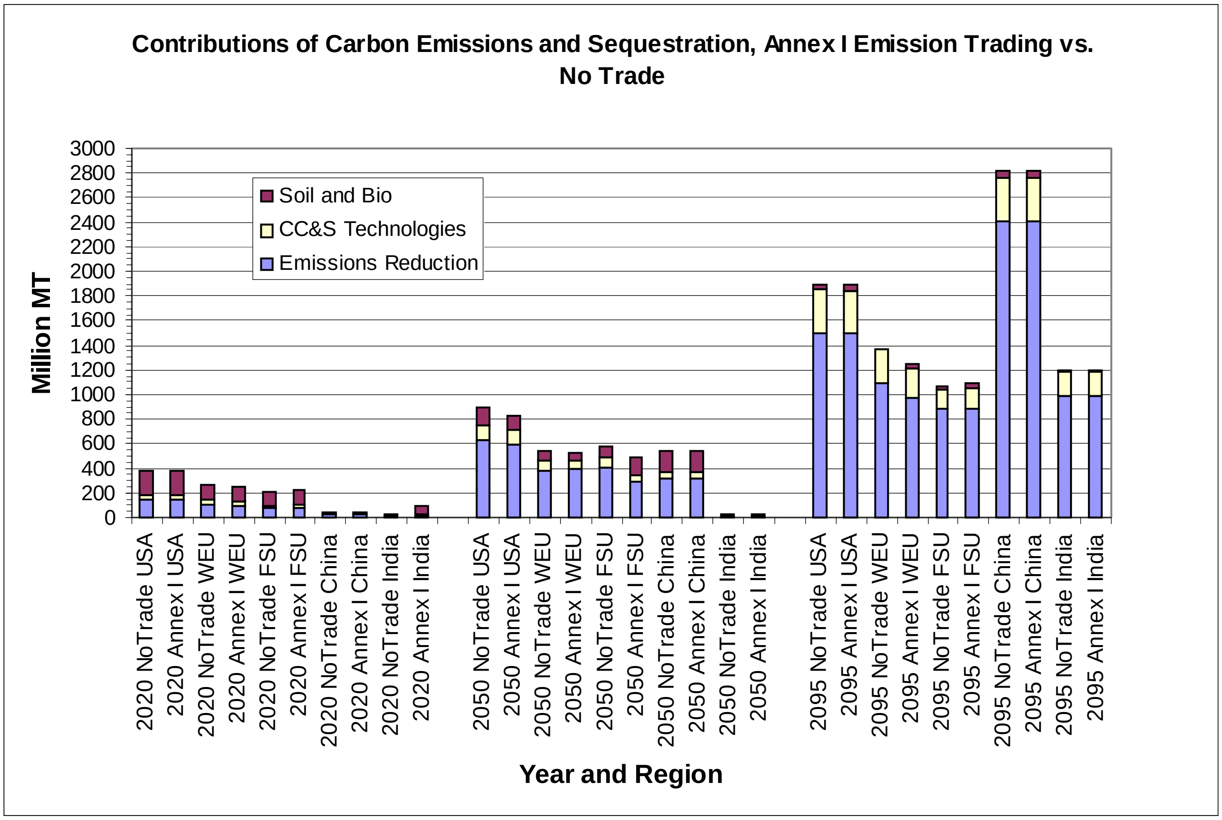

Figure 3. Emissions Reduction, CC&S, and Biological Sequestration for Selected Regions, WRE550 Annex I Trade vs. No Trade

Although the total emissions reductions are the same as in the No Trade Case, Annex I trading moves some of the regional emissions savings to different regions, as shown in Figure 3. Figure 3 shows that the U.S. and Western Europe both undertake less emissions reduction and less domestic sequestration, while the countries of the Former Soviet Union undertake more soil sequestration, but less emissions reduction and other CC&S in 2050 and more emissions control in 2095. Figure 3 does not show Canada, Australia, or Japan, all of whom undertake slightly more sequestration and slightly more emissions reduction with Annex I trading than without. Figure 4 shows that trading permits among Annex I countries results in some savings relative to independent compliance for the high cost controllers (all Annex I countries have the same marginal costs with Annex I trade). However, combining Annex I trading with CC&S technologies reduces marginal costs still further. Because the non-Annex I countries are not involved in the market for permits, their emissions and emissions costs are as before. The biological and soil sequestration peaks at about 940 million metric tons per year in 2035, then slowly declines to 175 million metric tons in 2095 as opportunities (mainly) within the Annex I countries are exhausted.

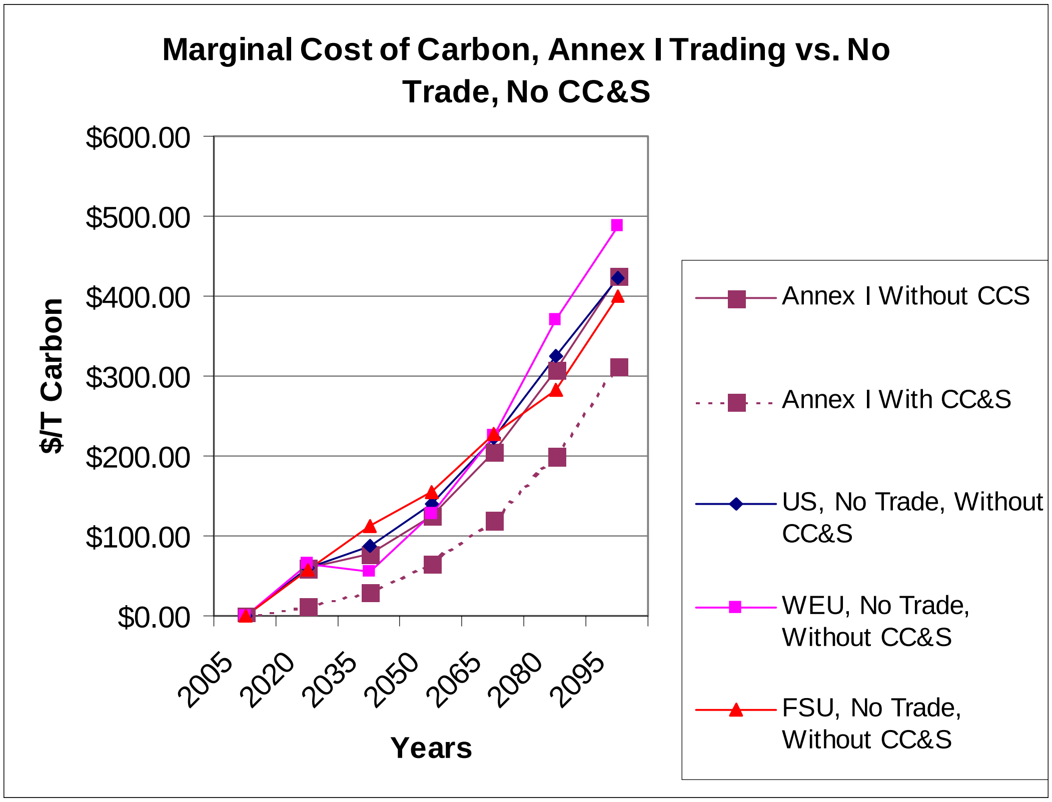

Figure 4. Marginal Cost of Carbon in Annex I Countries with Annex I Trade, Compared to the No Trade Case for WRE550.

Table 6 shows how total mitigation obligation costs are affected by trading and CC&S technologies together. For the United States, sequestration reduces total obligation costs by 60% in 2050, and by about 30% in 2095. Annex I trading saves about 1% to 3% more. The impact of trading is more important in Europe, since the region is a relatively higher cost controller. Western Europe is 6% better off with trade in 2050, and 3% better off in 2095 with trade than without. The world as a whole saves around $613 billion in control costs by 2095, roughly 30% of the baseline amount. The negative pressure from carbon control on national economies is also much reduced, saving about 1.7% of world GDP. The relatively small contribution of Annex I trading occurs because the marginal control costs of the major Annex I countries, very different among countries today, have converged by 2020. There is relatively little scope for cost reduction from trading permits among Annex I countries as a result.

Annex I GDPs are also generally higher that in the No Trade case. This generally benefits the economies of the non-Annex I countries even though they are not directly involved in the trade in permits or carbon sequestration. International fuel prices are about the same as in the No-Trade Case. As a result, energy-exporting regions, such as the Middle East, also export slightly more fossil fuel and have slightly higher GDPs.

Table 6. WRE550: Savings in Total Mitigation Obligation Cost by Region, with and without Sequestration and Annex I Emissions Trading, 2020, 2050, 2095 (Billion 1997 US$)

	2020		2050		2095	
Savings Due to Sequestration Only						
USA	$ 8.9	93%	$ 26.4	58%	$ 75.4	30%
WEUR	$ 6.4	91%	$ 14.6	61%	$ 57.2	26%
FSU	$ 4.8	94%	$ 17.3	49%	$ 39.4	29%
All Annex I	$ 26.1	93%	$ 67.5	57%	$ 235.4	31%
China	$ (0.0)	0%	$ 6.8	67%	$ 47.5	29%
India	$ 1.1	100%	$ 0.0	90%	$ 50.8	37%
All Non-Annex I	$ 9.3	82%	$ 48.8	51%	$ 360.4	28%
World	$ 35.4	90%	$ 116.2	54%	$ 595.8	29%
Savings Due to Annex I Trade Only						
USA	$ 0.0	0%	$ 0.7	2%	$ 0.1	0%
WEUR	$ 0.0	0%	$ 1.5	6%	$ 6.5	3%
FSU	$ 0.1	1%	$ 0.1	0%	$ 4.3	3%
All Annex I	$ 0.1	0%	$ 7.3	6%	$ 15.0	2%
China	$ (0.0)	-1%	$ 0.0	0%	$ 0.1	0%
India	$ (0.0)	0%	$ (0.0)	-1%	$ 0.0	0%
All Non-Annex I	$ (0.0)	0%	$ 0.1	0%	$ 0.2	0%
World	$ 0.1	0%	$ 7.4	3%	$ 15.2	1%
Savings Due to Annex I Trade and Sequestration						
USA	$ 8.9	93%	$ 26.8	59%	$ 75.7	30%
WEUR	$ 6.5	92%	$ 14.6	61%	$ 62.4	28%
FSU	$ 4.8	94%	$ 20.1	56%	$ 39.4	29%
All Annex I	$ 26.1	93%	$ 73.5	62%	$ 252.2	33%
China	$ (0.0)	-80%	$ 6.8	68%	$ 47.5	29%
India	$ 1.1	100%	$ 0.0	90%	$ 50.9	37%
All Non-Annex I	$ 9.3	82%	$ 48.8	51%	$ 360.4	28%
World	$ 35.4	90%	$ 122.3	57%	$ 612.6	30%

Note: Marginal Abatement Cost is shown in Figure 4 for the Annex I countries. Marginal costs of carbon for Non-Annex I countries are the same as in Table 3.

World Trading Case

The gains from emissions trading are potentially much greater if the group of nations undertaking reductions could be expanded to include the non-Annex I countries as well as the Annex I countries. Although non-Annex I countries currently have no obligation to control GHG emissions, this hypothetical case treats non-Annex I countries as if they agreed to create permits equal to their annual base case emissions and allowed these permits to be traded internationally. World trading with sequestration shows low marginal carbon control costs for Annex I countries ($52.24/ton in 2050, for example, in contrast to $64/ton with Annex I trading or between $63/ton and $108/ton with no trading).

However, there are significant implications for CC&S technologies, especially in the Organization for Economic Cooperation and Development (OECD) countries. Because world trading greatly reduces the marginal cost of emissions abatement available to these countries through trade, much less domestic CC&S is undertaken. At the same time, the scope for low-cost CC&S in the non-Annex I countries is expanded because there is an additional market for such activity in the Annex I countries.

Figure 5 illustrates the change in emissions control by source for selected world regions with world trade in carbon emissions. Figure 5 shows that, during the intermediate period (2020 to 2050) when sequestration is particularly important, the U.S., Western Europe, and Former Soviet Union all reduce carbon emissions to a lesser degree (emit more carbon) than if trade were not permitted, and the U.S. and Western Europe also undertake less sequestration. China and some of the other non-Annex I countries make up the difference by undertaking significantly more emission abatement and also a significant amount of sequestration on behalf of the Annex I countries. The biological and soil squestration component peaks at about 1,200 million metric tons per year in 2020 thanks to the participation of non-Annex I countries, then slowly declines to 225 million metric tons in 2095 as world-wide opportunities are exhausted. By the end of the century, most low-cost sequestration opportunities have been exhausted, and all parties meet their obligations by reducing emissions and undertaking more costly CC&S. However, even under these conditions, Western Europe emits more carbon and China emits far less carbon when emissions trading is allowed than when it is not.

Table 7 illustrates the effects on total obligation costs. The impact of world trading on world control costs of emissions is considerably greater than that of Annex I trading because the disparity between marginal control costs is greater world-wide than it is within the Annex I countries. Thus, in 2095 world trading adds about 20% to the cost reductions achievable through sequestration alone. The separate impacts of trade and sequestration are also shown in the table. Since the trade reduces sequestration in some regions and increases it in others, the net impact is actually slightly less than the sum of the effects.

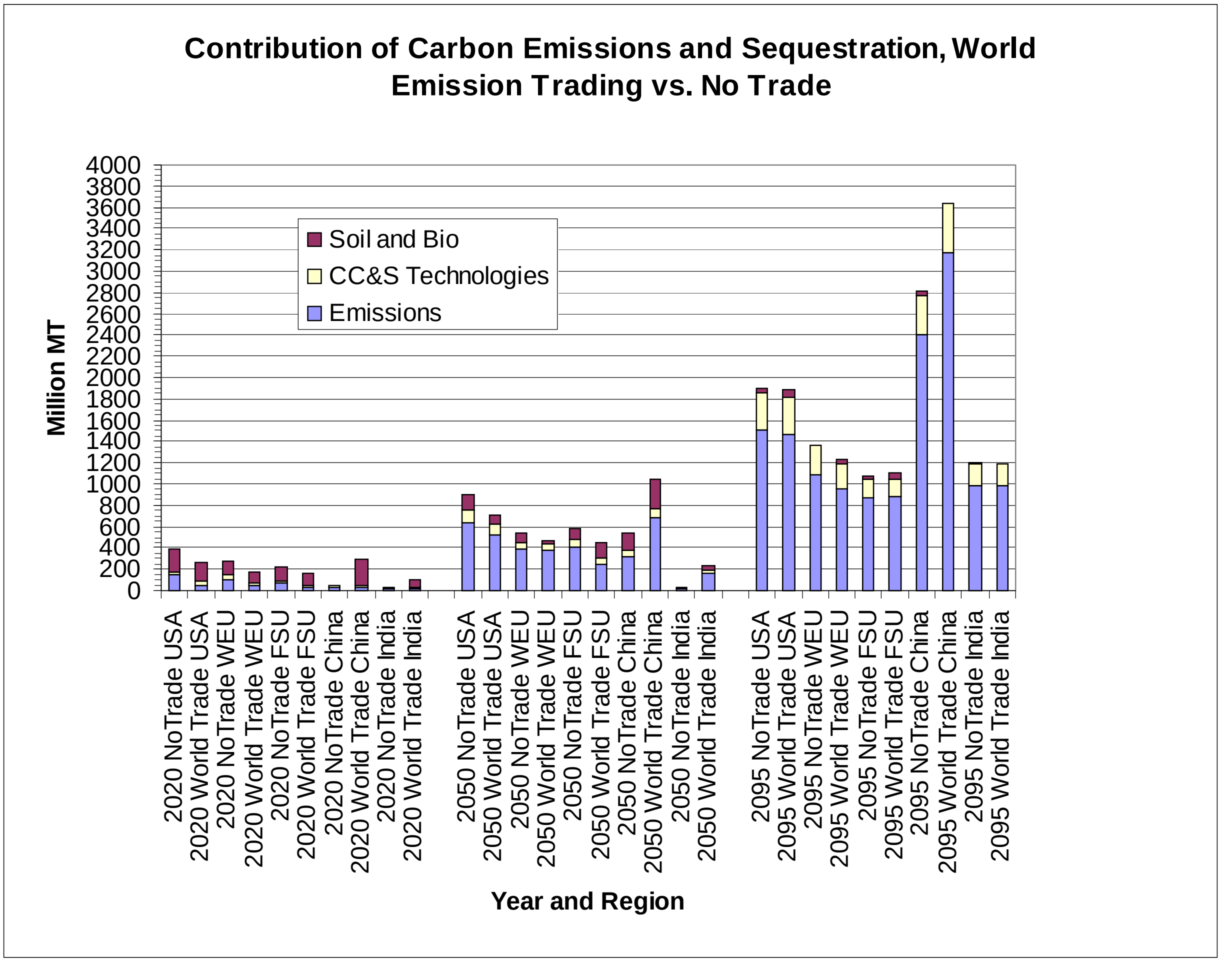

Figure 5. Emissions Reduction, CC&S, and Biological Sequestration for Selected Regions, WRE550 World Trade vs. No Trade

Table 7. WRE550: Savings in Total Mitigation Obligation Cost by Region, With and Without Sequestration and World Emissions Trading, 2020, 2050, 2095 (Billion 1997 US$)

	2020			2050			2095		
Savings Due to Sequestration Only									
USA	$	8.9	93%	$	26.4	58%	$	75.4	30%
WEUR	$	6.4	91%	$	14.6	61%	$	57.2	26%
FSU	$	4.8	94%	$	17.3	49%	$	39.4	29%
All Annex I	$	26.1	93%	$	67.5	57%	$	235.4	31%
China[a]	$	(0.0)	*	$	6.8	67%	$	47.5	29%
India	$	1.1	100%	$	0.0	90%	$	50.8	37%
All Non-Annex I	$	9.3	82%	$	48.8	51%	$	360.4	28%
World	$	35.4	90%	$	116.2	54%	$	595.8	29%
Savings Due to World Emissions Trading Only									
USA	$	1.3	13%	$	4.7	10%	$	4.6	2%
WEUR	$	1.2	17%	$	2.1	9%	$	10.0	5%
FSU	$	0.5	10%	$	7.0	20%	$	4.1	3%
All Annex I	$	3.7	13%	$	15.3	13%	$	32.0	4%
China[a]	$	5.1	*	$	13.3	133%	$	91.8	56%
India[a]	$	0.1	8%	$	10.5	*	$	1.3	1%
All Non-Annex I	$	9.1	80%	$	55.6	58%	$	466.1	36%
World	$	12.7	32%	$	70.9	33%	$	498.2	24%
Savings Due to Sequestration with World Emissions Trading									
USA	$	9.5	99%	$	28.0	62%	$	80.1	32%
WEUR	$	7.0	99%	$	15.2	64%	$	67.8	31%
FSU	$	5.0	99%	$	21.9	61%	$	43.2	31%
All Annex I	$	27.8	99%	$	76.0	65%	$	266.3	35%
China[a]	$	(0.0)	*	$	12.3	123%	$	120.7	74%
India[a]	$	1.1	100%	$	4.0	*	$	51.5	37%
All Non-Annex I	$	11.3	99%	$	74.5	77%	$	738.0	58%
World	$	39.1	99%	$	150.4	70%	$	1,004.3	49%

[a] China's impacts from trade are all very small changes to a value that is near zero. A similar small change occurs in India in 2050.

In the world trading case, the world fossil fuel prices are higher and the GDP of trading partners is higher than when no trading of permits is allowed. The non-Annex I countries significantly reduce domestic economic production. They are more than compensated for this with international payments for carbon reduction from the Annex I countries equal to roughly 2% of GDP. Although these payments are a source of wealth, they are not counted in GDP since they are international payments. Although the non-Annex I countries might realize a net increase in wealth from these payments, the ultimate recipients of the payments are unlikely to be the same as the those earning wages in the general economy as captured by the GDP statistic; thus, the potential exists for difficult economic distribution problems in the countries receiving such payments.

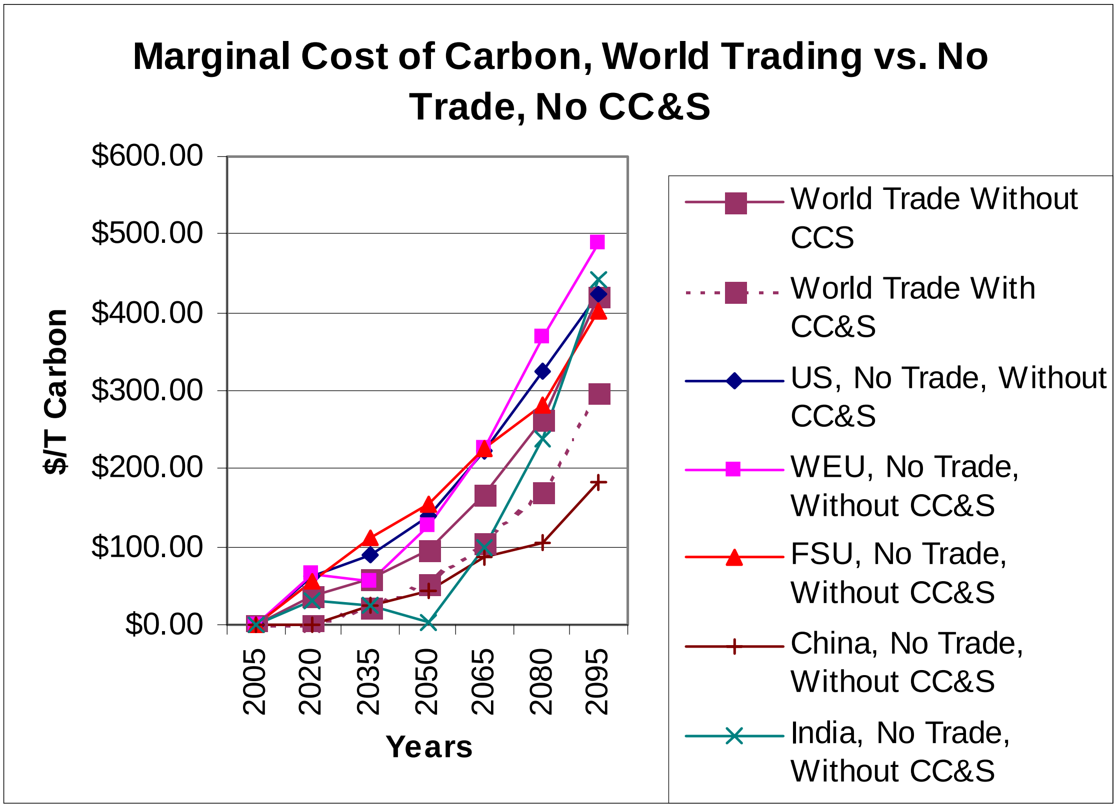

Figure 6. Marginal Cost of Carbon in World with World Trade, Compared to the No Trade Case for WRE550.

Effects of Temporary Sequestration

Carbon capture is not the activity that mitigates climate change. Rather, it is the sequestration of greenhouse gases from the atmosphere that slows or prevents global warming. To this point in the paper, we have assumed that sequestration actions are permanently effective. However, many of the proposed sequestration options are known to be temporary in nature, because they rely on isolating greenhouse gases in soils, biomass and the ocean, where these gases have the potential to leak back into the atmosphere. This happens, for example, when soils are disturbed, trees are harvested, or the ocean re-emits the carbon stored there. Even geologic sequestration is believed to be temporary. To achieve a given emissions trajectory, such as WRE550, additional mitigation actions are needed to offset the releases due to imperfect sequestration.

Although there is considerable uncertainty about the long-term effectiveness of sequestration, the following assumptions will serve to illustrate the potential importance of temporary sequestration. To perform the assessment, we first assume the upper bound estimates of potential sequestration provided by I.R. Noble and R.J. Scholes in “Sinks and the Kyoto Protocol” (Noble and Scholes 2001), in turn based on Schlamadinger and Kjarlainen (2000) and Sampson and Scholes (2000). The principal long-term carbon sequestration options come under Article 3.4 of the United Nations Framework Convention on Global Climate Change (UNFCCC), "improved land management" as "deliberate changes in land use." The Noble and Scholes upper bound estimate of 2.2 billion metric tons is higher than the combined sequestration due to CC&S technologies and biological sinks under any of the three cases considered in the previous section. Also the release rate for biological sinks may be higher than that for some of the geological sinks included in the CC&S technologies. Hence analysis of the Noble and Scholes scenario gives the maximum possible impact of imperfect sequestration. Based on discussions with scientists engaged in sequestration research, it is estimated that at most 5% *per year* of carbon sequestered begins to leak back into the atmosphere after 50 years in place. The impact is to increase the amount of carbon abatement and capture that must be accomplished late in the 21st Century.

Maximum cumulative sequestration occurs in 2095 at about 185 billion metric tons of carbon, and then begins to decline unless effort is undertaken to maintain the stock. Without such effort releases of sequestered carbon must decline rapidly after 2100. Even though the MiniCAM model does not extend beyond 2095, making it impossible to directly calculate control costs in the 22nd Century, it is possible to calculate the cumulative sequestration, the releases and the allowed emission rate with perfect and imperfect sequestration through 2195. Figure 8 shows cumulative sequestration for both the WRE550 case with world emissions trading, and for the maximum sequestration case if sequestration is temporary. The net sequestration rates are set at zero in Figure 8 after 2095 to show the effects of leakage. Both cases are also shown without leakage. In effect, leakage would be a new (and growing) source of anthropogenic emissions of carbon over which the countries of the world have no direct control. Their recourse is assumed to be additional abatement of emissions sources and additional CC&S activity necessary to offset imperfect sequestration and retain the WRE550 pathway of carbon concentrations.

Roughly 4.4 billion additional metric tons of carbon per year in sequestration would offset the effects of leakage and hold cumulative sequestered carbon at 2095 values. Equivalently, emissions could be reduced that much more. At $300/T, the additional cost would amount to $1trillion per year, almost doubling the total cost of $1.4 trillion in that year. The additional costs involved in meeting these additional obligations also provide a metric of the value of any new technology that could make the sequestration permanent. There is no diffference in total compliance cost as late as 2050 if sequestration is temporary as described; but the difference is about a $20 billion increase (2%) by the end of the 21st century, which continues to rise over time. Thus, the impacts of impermanent sequestration on carbon abatement or its cost will not be significant until the 22nd century, although they would be rising by the end of the 21st century. Offsetting temporary sequestration could be a very significant addition to the cost of abatement in the 22nd century.

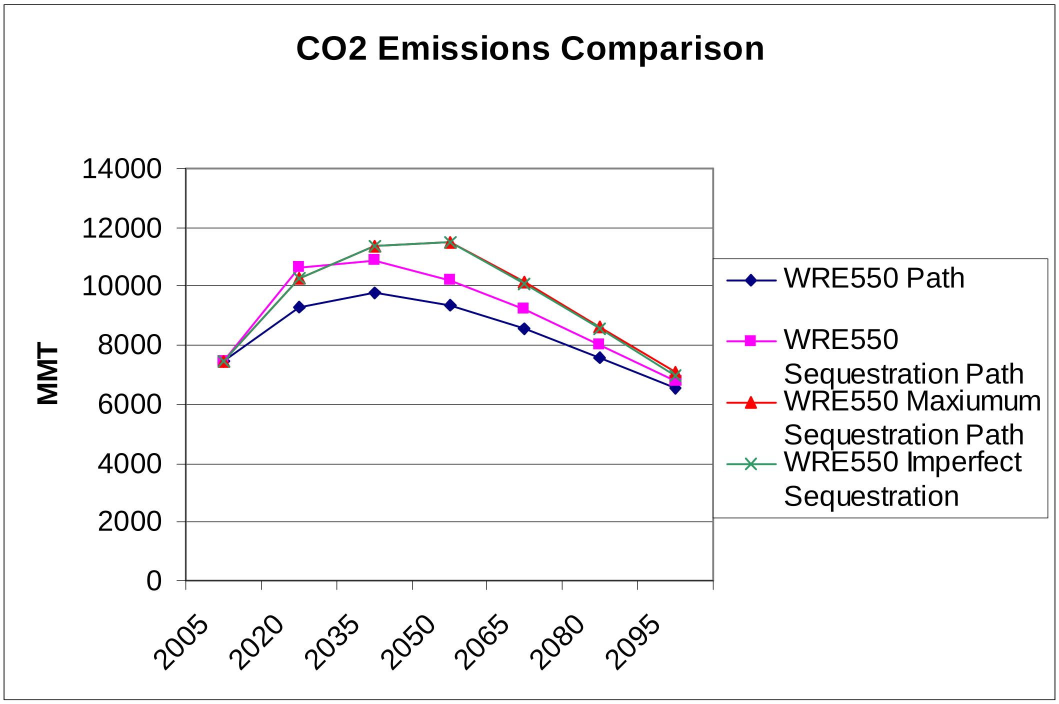

Figure 7. Impact of Temporary Sequestration on the Carbon Dioxide Emissions Pathway

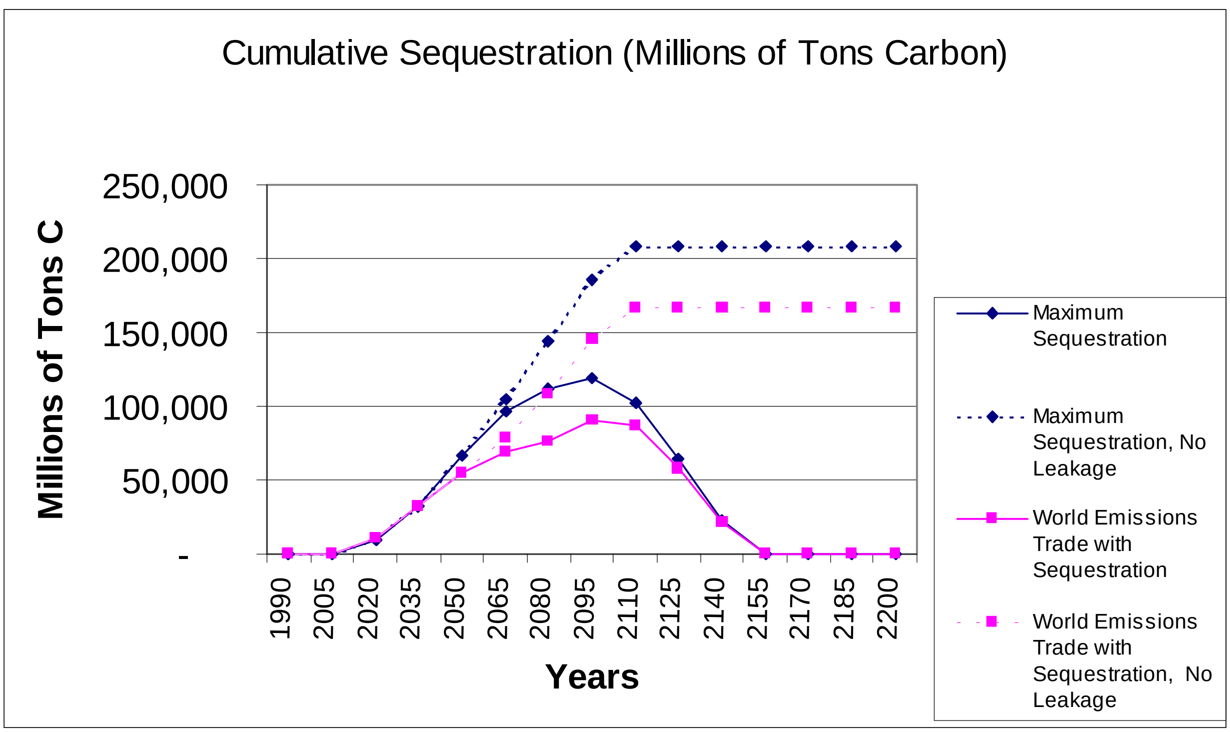

Figure 8. Cumulative Carbon Sequestered with Temporary Sequestration

Summary of CC&S and Trade Effects

The impact of sequestration options on carbon management is strongly influenced by the presence or absence of the ability to trade carbon emissions permits and credits. Although the amounts of carbon sequestered may not be large in comparison to the amounts abated by other means, CC&S technologies contribute in a very important way to reducing the marginal cost of carbon, in many cases reducing it by nearly two-thirds. Figure 9 summarizes the impacts of emissions trading on carbon sequestration. Initially the sequestration is dominated by soils and biological sinks because of their low costs. This continues through 2050. The capacity of these sinks is mostly exhausted shortly afterward. At the same time CC&S technologies become more competitive due to the assumed performance and cost improvements and increases in marginal compliance costs. Thus, by 2095 the CC&S technologies are the dominant sequestration technologies.]

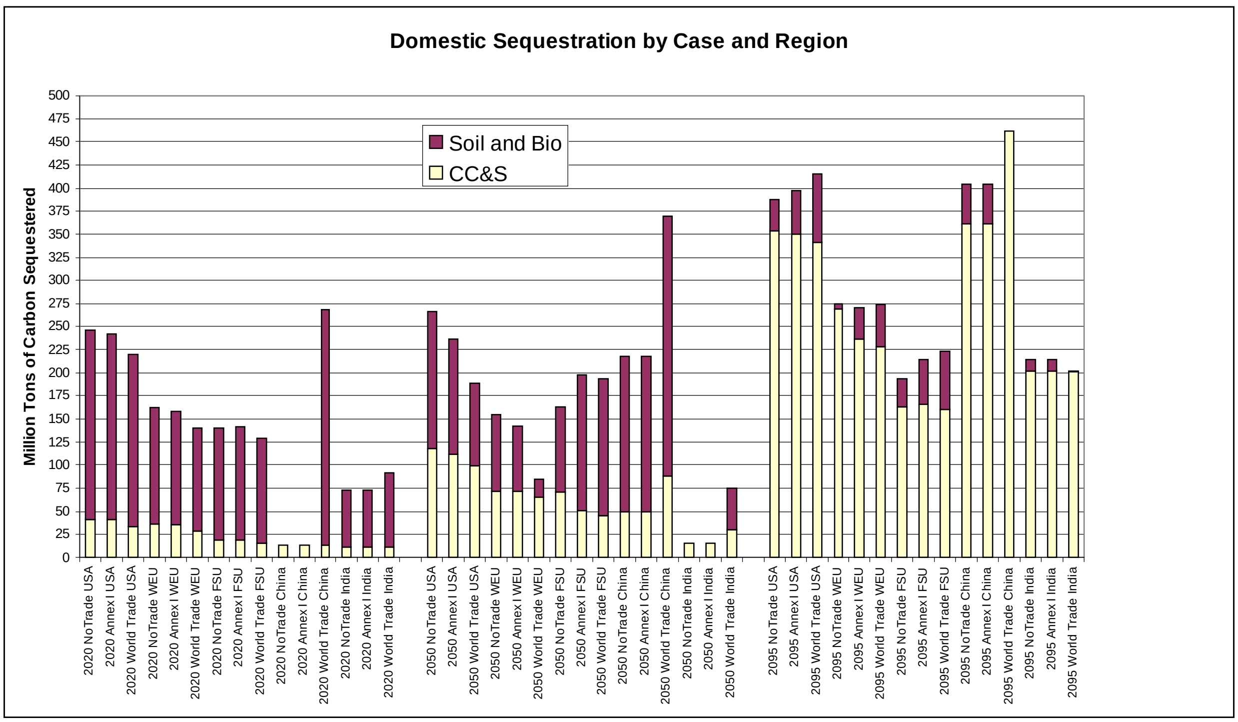

Figure 9. Impact of Emissions Trading on Carbon Removed and Sequestered by CC&S Technologies

Results and Conclusions

The paper has demonstrated that using sequestration options to satisfy emissions can significantly reduce the cost of stabilizing the carbon content of the earth's atmosphere. Allowing limitation obligations to be traded in addition will affect the value of carbon and thereby the timing, magnitude, cost, and location of CC&S technology deployment. International trading of emissions permits has an effect equivalent to relaxing cost constraints that competes with CC&S technology. Thus, implementation of some flexibility mechanisms may lead to later deployment of CC&S technologies, while early constraints on emissions might lead to their more rapid introduction in the Annex I countries.

There was only a small reduction in CC&S deployment between the No Trade and Annex I trading cases. The paper shows that Annex I trading provide compliance cost savings of about 2 to3 percentage points on top of the 30% savings associated with deployment of CC&S technologies, while world trade in emissions increases savings by about 20 percentage points. With world trade, the distribution of abatement and sequestration increase by 5% and 7%, respectively by 2095, and activity moves toward non-Annex I countries. Because GDP in some non-Annex I countries is reduced by abatement undertaken on behalf of Annex I countries, distribution of the associated international payments within these non-Annex I countries could be an issue of considerable importance.

Given what is currently known about the impermanence of sequestration, the impacts of impermanent sequestration on carbon abatement or its cost will not be significant in the 21^{st} century, although they could add considerably more to the cost of abatement in the 22^{nd} century.

Future Activities

The knowledge base on sequestration activities, particularly their effectiveness and cost, and particularly in the developing world, remains very limited at this time. Future research needs to be directed at improving the knowledge base concerning CC&S technologies.

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Endnotes

[1] Annex I parties to the United Nations Framework Convention on Climate Change (UNFCC) consist of 36 developed countries and economies in transition that originally

agreed at the "Earth Summit" in 1992 to stabilize their CO_2 emissions at 1990 levels by the year 2000. These countries include Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Czechoslovakia, Denmark, European Union (note that individual countries comprising the EU are also listed independently), Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States of America.

Annex II parties consist of 25 developed countries (Annex I parties minus the economies in transition). These countries include: Australia, Austria, Belgium, Canada, Denmark, European Union, Finland, France, Germany, Greece, Iceland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom of Great Britain and Northern Ireland, and the United States of America.

Non-Annex I countries are the remaining countries of the world.