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2008

11th Annual High School Mathematical Contest in Modeling (HiMCM) Summary Sheet
(Please attach a copy of this page to each copy of your Solution Paper.)

Team Control Number: 2113
Problem Chosen: B

Please type a summary of your results on this page. Please remember not to include the name of your school, advisor, or team members on this page.

Stuck in Neutral

At the 2008 G8 Summit, President George W. Bush signed an agreement to halve carbon emissions in the United States by 2050. Though a step in the right direction, the United States still has far to go to mitigate the effects of global warming. Since it is not yet technologically possible to reduce the level of emissions to zero, the long term goal is to achieve carbon neutrality by consuming the same amount of carbon that we produce, which accumulates in our atmosphere over a period of time. Our task is to provide the most feasible solution for the latter option and evaluate its cost and effectiveness, assuming emissions are capped at 2007-2008 levels.

The largest source of anthropogenic carbon dioxide emissions in the United States is the consumption of fuel. This releases carbon dioxide directly into the air, and the only method to sequester this carbon is through the photosynthetic processes of plants. Therefore, the first portion of our model analyzes the efficiency of a massive reforestation campaign throughout the continental United States. The second major source of carbon emissions comes from producing electricity – a process that uses coal, natural gas, and petroleum. For this, we propose retrofitting the existing fleet of coal and natural gas-fired power plants in the United States with carbon capture and storage technology and depositing the carbon at a depth of 3000 meters in the ocean. Since feasible technology currently does not exist for capturing carbon in petroleum-fired power plants, those emissions will be accounted for by reforestation. The second portion of our model provides an analysis for retrofitting and diverting carbon dioxide from these power plants.

According to our model, the forests will cease to sequester carbon after roughly 155 years. Using all the feasible land in the United States, we found that reforestation only sequesters 151,215.8 million metric tons of carbon out of the 989,689 million metric tons produced by the United States over the same time span, at a cost of 30.2 trillion dollars. (For sake of comparison, the national debt is 10.6 trillion US dollars). While we can achieve carbon neutrality for the electricity production sector at price 202.8 billion dollars, we cannot effectively achieve carbon neutrality at the national level through our 30.3 trillion dollar plan. We conclude that carbon neutrality cannot be feasibly achieved by merely increasing consumption of carbon dioxide.

Table of Contents

Stuck in Neutral

1. Restatement of the Problem

The problem has two components. First, we must find the optimal solution for achieving carbon neutrality, assuming that emissions are capped at 2007-2008 levels. The solution we provide must minimize economic and cultural impacts. Second, we must model our solution to show cost, feasibility, and effectiveness.

2. Problem Analysis

There are two chances to sequester carbon: pre-combustion and post-combustion. Pre-combustion carbon capture technology is currently available for retrofitting coal-fired and natural-gas fired power plants. Post-combustion sequestration must take place through biological processes of plants. Thus, our solution must address both of these areas.

Carbon neutrality can be evaluated as a sum of annual carbon emissions and annual carbon consumption, or the sum of total carbon accumulated over time period *t* and total carbon consumption over a time period *t*. Both methods are equally valid because at some point, the net carbon produced over time will be zero.

3. Solution

Carbon sequestration contains a broad and multi-faceted array of options for execution. Choices include terrestrial sequestration, subterranean sequestration, retrofitting electricity production facilities with carbon dioxide capture capability, ocean sequestration by way of direct injection, ocean sequestration through iron fertilization, and ocean sequestration through dissolution.

We chose to use retrofitting coal and natural gas facilities, deep ocean injection, and terrestrial sequestration. Retrofitting coal and natural gas plants was the best option to deal with the emissions from each. The only alternative given available landmasses would be to destroy all coal and natural gas plants that emit carbon dioxide, which is clearly ridiculous. Retrofitting has no cultural impact because there is literally no culture surrounding the production of electricity. Minimal change of lifestyle will be required however as the United States will either have to cut programs or raise taxes in order to execute the plan without increasing the deficit. We chose deep ocean injection because it lacks the problems associated with any other final destination for the carbon from coal and natural gas electricity, such as ocean acidification, when used in tandem with a terrestrial carbon sequestration program. It also has the potential to remain effective for hundreds of years, making it cost effective over the long term. It avoids cultural destruction because it will not encroach on the practice of traditions. The alternative, iron fertilization of phytoplankton, violates an international treaty and has the potential to worsen the climate. Ocean sequestration through dissolution lacks the permanence of deep ocean injection and was disregarded because our model embraces a consideration of the future within the constraints of the problem. Subterranean sequestration at its present state can poison groundwater, which immediately means that it has the potential to disrupt cultures and economies by rendering water unusable or expensive to treat. Terrestrial sequestration was chosen because it can be done without causing major environmental damage. Our plan for terrestrial sequestration is of reforestation, not deforestation; therefore, every tree removed will have one or more in its place.

4. Assumptions and Justifications

A1. ***U.S. carbon dioxide emissions are capped at 2007-2008 levels***
J1. This is given in the problem prompt.
A2. ***Mass reforestation is limited to the forty-eight continental states.***
J2. The climates in Alaska and Hawaii are so distinct from the continental United States that it does not support the three types of trees we chose for reforestation.
A3. ***The government is able to reforest land that is already forested and land set aside for special uses.***
J3. Land includes timberland, reserved land, and other non-Federal area; this is necessary to enable maximum carbon sequestration.
A4. ***Cost is a function of tons of carbon mitigated rather than a function of the type and number of trees.***
J4. This simplifies the model and eliminates two variables, making for easier comparison.
A5. ***Forests are maintained indefinitely, without risk of damage by fire or pests or decay*.**
J5. Maintenance fees are already accounted for in our model; fire, pests, and decay pose a potential risk for increased carbon emissions.
A6. ***The process of reforestation is carbon neutral*.**
J6. Accounting for increased carbon emissions while increasing carbon consumption over-complicates our model
A7. ***Government subsidizes all costs of electricity***
J7. There is no net increase in the price of electricity for the consumer because the problem prompt implies government action.
A8. ***Changes in cost due to inflation are minimal***
J8. Dollar values and approximations are consistent with current prices to retain accuracy of values. Dollar values are solely for comparison purposes.
A9. ***All coal plants in the United States agree to having to their plants retrofitted; retrofitted plants sequester 100% of carbon.***
J9. Maximum location and effectiveness allows us to assume the maximum amount of carbon sequestration and evaluate whether carbon neutrality is even possible.
A10. ***Only energy-related carbon emissions contribute to carbon footprint.***
J10. This allows us to exclude natural and non-anthropological sources of carbon such as breathing.
A11. ***'Ton' refers to an American short ton, whereas 'Tonne' refers to a metric ton.***
J11. Different sources provided different uses of the word ton (Metric Ton). By assuming association of specific spellings with specific terms, we were able to covert data appropriately.
A12. ***All graphs used in data collection are precise and perfectly to scale*.**
J12. Our methods of pixel counting and integration are dependent on the accuracy and precision of graphics.
A13. ***All trees are planted at the same time*.**
J13. Adding the variable of when the trees are planted would lead to a gigantic number of possible scenarios, thus making a model and integration impossible.
A14. ***Trees are planted on a permanent basis with no harvesting or rotations.***

J14. Theoretically, we can achieve higher levels of sequestration. However, that depends upon the decay rates of plant matter in the soil – a variable is difficult to collect data and also would complicate our model.

5. Development of Model

I. Terrestrial Carbon Sequestration

This is the largest component of our plan and has to account for the most carbon dioxide emissions. For our reforestation campaign, we divided the United States into three regions. Each region will grow a different species of tree that is most suited to the climate while optimizing the amount of carbon the tree can sequester. We chose the loblolly pine, the black walnut, and the ponderosa pine as the trees for our plan because the most data was available for these three species.

According to a study by Richards in 2004 shows that the trees have a time where the rate of carbon intake peaks and then begin approach zero as age increases – the behavior of a logistical function (Figure 1).

A DECADE OF FOREST CARBON SEQUESTRATION COST STUDIES 9

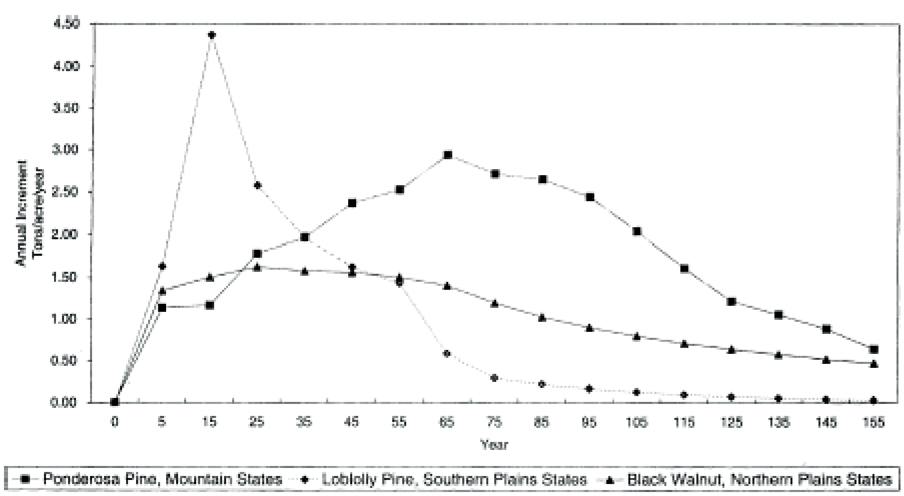


Figure 1. Carbon sequestration rates in the United States for three region/species combinations.

No actual raw data was provided other than this graph, however, we could still use the graph to approximate data using pixel counting technology. More on our method can be found in the appendix.

To find the amount of carbon dioxide each type of tree absorbs after 155 years, we approximated the integral of the rate of sequestration for each species over the time period using pixel counting technology.

To find the maximum amount of land in the continental US we could plant these trees, we looked at a study of major land use by the United States Department of Agriculture and allotted all land currently used for forests and special uses to be reforested with the respective type of tree in our plan.

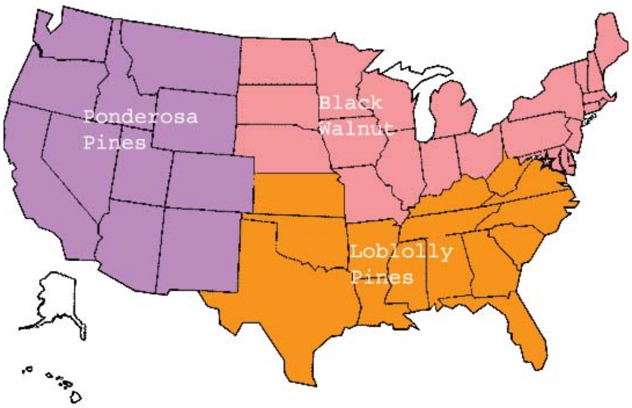


Figure 2 – Reforestation species by region

- For the region growing black walnut trees (sha ded pink), we found that **220.7 acres** are available.
- For growing loblolly pines (shaded orange**), 272.8 acres** are available.
- For growing ponderosa pines (shaded purple), **315.5 acres** are available.

As for the cost of reforesting this land, we turn to the scholars of our past. There have been multiple studies of the cost of US forest based carbon sequestration as summarized by Richards and Stavins in 2005. After critically evaluated several studies, we determined that Stavin's econometric model published in 1999 provided the best data for our model. This is because Stavins takes into account the behavior of landowners when faced with the decision whether to relinquish their land. So even though his cost per ton of carbon mitigated maybe higher than some other studies, it is more realistic than others because it is more sensitive to behavior that is difficult to quantify. According to Stavins, the cost in US dollars to sequester one short ton of carbon dioxide is $181.13 or $199.66 per metric ton.

If we let our variables be:

R_{s1} = the function of carbon dioxide sequestered by an acre of ponderosa pines over time
R_{s2} = the function of carbon dioxide sequestered by an acre of loblolly pines over time
R_{s3} = the function of carbon dioxide sequestered by an acre of black walnut trees over time
A_1 = the land area available in the ponderosa pine growing region in acres
A_1 = the land area available in the loblolly pine growing region in acres
A_1 = the land area available in the black walnut trees growing region in acres
T = the cost of sequestering one metric ton of carbon dioxide according to Stavins
C_t = the cost to sequester varying amounts of metric tons of carbon

Our model of the cost to sequester any amount carbon dioxide in metric tons over 155 years is a function of acres of each type of tree planted in each of the three regions:

$$C_t = T\left[(\int_0^{155} R_{s1})A_1 + (\int_0^{155} R_{s2})A_2 + (\int_0^{155} R_{s3})A_3 \right]$$

II. Carbon Capture Sequestration

A. Coal-Based Power Plants

We based our model of the cost of retrofitting CCS technology for coal-fired plants using the DOE-NETL study of an existing retrofitted coal-firing power plant of Conesville Unit #5 in Ohio. Of the 4 cases studied, 90% was the highest percentage of carbon capture that was studied.

We take their data (Figure 4.1) and extrapolate to 100% carbon capture using a linear regression. The linear regression was chosen because the authors of the study indicated in the study that their existing data already exhibited a linear relationship. (Figure 4.2)

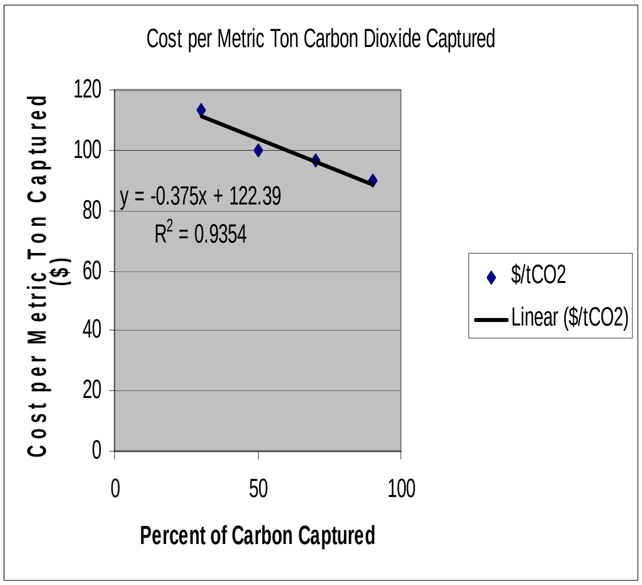


Figure 4.2 – Extrapolation of 100% carbon capture cost using linear regression

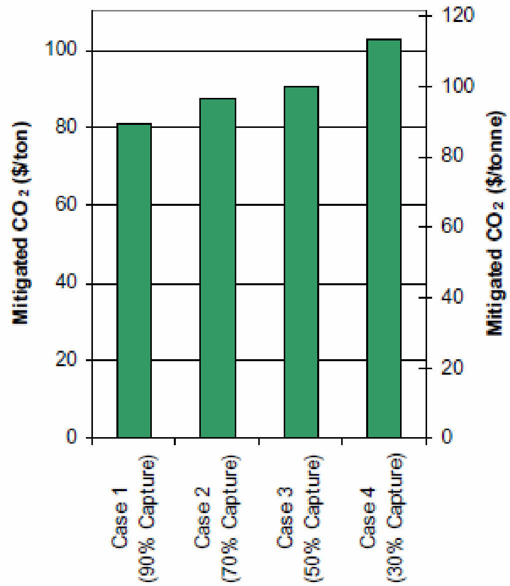


Figure 4.1 – cost per ton of captured CO_2

If we let our variables be:

C_c= total cost to capture carbon due to coal-based electricity production
s_1= the amount of carbon emitted by coal-based power plants in metric tons
R_c = the cost per ton of carbon mitigated from the previous extrapolation

Our model for the cost to neutralize emissions for coal-fired power plants across the United States will be $C_c = R_c s_1$.

B. Natural Gas – Based Power Plants

According to another study done by the NETL, the cost to capture one ton of carbon dioxide in a natural gas-fired power plant is $83.00 or $91.49 per metric ton of carbon dioxide captured. We can use the same methodology in Section IA to model the cost of retrofitting these plants.

If we let our variables be:

C_{ng}= total cost to capture carbon due to coal-based electricity production
s_2= the amount of carbon emitted by coal-based power plants in metric tons
R_{ng}= the cost per ton of carbon mitigated from the previous extrapolation

Our model of the cost to neutralize emissions for natural gas-fired power plants across the United States will be $C_{ng} = R_{ng} s_2$.

C. Cost of Deep Ocean Injection

According to the R&D division of McDermott Technology, Inc, the estimated costs for transport and storage of captured carbon dioxide in liquid form in the ocean at a depth of 3000 meters is $3.20 per metric ton.

If we let our variables be:
C_d= total cost to inject captured carbon due to coal-based electricity production
R_d= the cost of ocean injection per metric ton

Our model for the cost of deep ocean injection of the carbon dioxide sequestered by the coal and natural gas based power plants will be $C_d = R_d\left(s_1 + s_2\right)$.

D. Total Cost to Retrofit Power Plants for Pre-combustion Sequestration

The total cost to retrofit coal and natural gas based power plants in the US is a summation of the three previous functions: $C_k = C_{ng} + C_c + C_d$.

III. Bottom – Line Cost of Plan

The final cost of our entire plan is the sum of the cost of carbon capture sequestration and terrestrial carbon sequestration:

$$C_{total} = C_k + C_t$$

6. Calculations

$$C_c = R_c s_1 = (84.89)*(1,937,870,000) = \$164,505,784,300.00$$

$$C_{ng} = R_{ng} s_2 = (91.49)*(339,530,000) = \$31,064,224,030.05$$

$$C_d = R_d\left(s_1 + s_2\right) = (3.196702802)*(1,937,870,000 + 339,530,000) = \$7,280,170,961.00$$

$$C_k = C_{ng} + C_c + C_d = (3.106*10\text{^}10) + (1.645*10\text{^}11) + (7.280*10\text{^}9) = \$202,850,179,291.05$$

$$C_t = T\left[(\int_0^{155} R_{s1})A_1 + (\int_0^{155} R_{s2})A_2 + (\int_0^{155} R_{s3})A_3 \right]$$

$$= 199.66*(10^6)\left[(257.2936)(315.5) + (134.3675)(272.8) + (151.2651)(220.7\ )\right] = \$30,191,745,100,000.00$$

$$C_{total} = C_k + C_t = \$30,394,595,280,000.00$$

7. Conclusion

According to the Energy Information Administration, the total energy-related carbon dioxide emission level of the United States in 2007 is 8222 million metric tons (MMT). Our plan is able to neutralize the 2277.4 MMT per year due to electricity production by coal and natural gas. Of the 5944.56 MMT remaining accumulated over the next 155 years – resulting in 989688.95 MMT – terrestrial carbon sequestration is able to solve for 151215.81MMT. That is 15.23% of the carbon dioxide neutralized. Our plan assumes the use of 42.7% of land in the continental United States – an idealistic hope already. In reality, the amount of land we have at our disposal is much less; therefore, we conclude that neutralization is not possible in the real world.

When evaluating the effectiveness of our plan, we must look at the two components separately. Carbon capture sequestration can theoretically be 100% effective and has been proven to be 90% effective. Studies done at MIT have shown the ocean has plenty of capacity to store liquefied carbon. Terrestrial based carbon sequestration can theoretically be 100% effective as well, given enough land area.

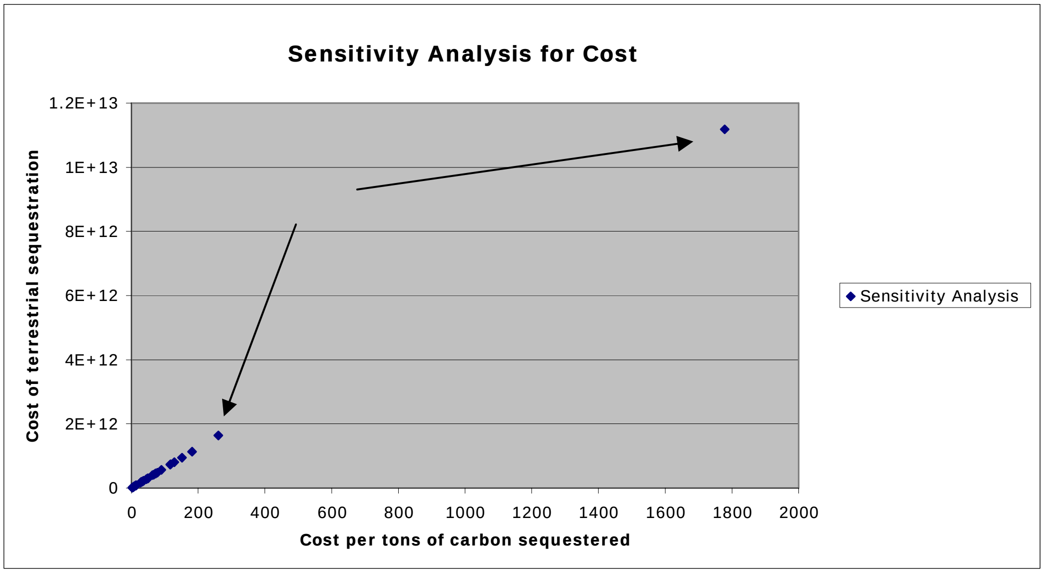
When evaluating feasibility, it is clear that carbon capture sequestration is feasible, but terrestrial carbon sequestration is not. The price tag of roughly 200 billion dollars is reasonable when weighing it against the environmental benefit of decreasing a portion of our emissions. Given the limited land area in the United States and the drastic nature of reforesting 42.7% of the U.S., using terrestrial carbon sequestration alone to account for the rest of U.S. emissions is not feasible.

When evaluating cost, our model at first glance seems inordinate with its high price tags. However, cost should be viewed through a paradigm that incorporates the non-monetary benefits of investing in increased carbon dioxide consumption. The start up cost of retrofitting the existing fleet of coal and natural gas based power plants is $89.07 per metric ton. Consequent years would only require maintenance and upkeep, making retrofitting a long-term investment in the welfare of the planet that we believe will be worth it. The same can be said for terrestrial carbon sequestration. With that process, it costs about $200 dollars to mitigate one metric ton of carbon. However, neutralizing even 15% of carbon emissions will mitigate negative effects of global warming and contribute to the overall health of our nation, global community, and the planet. Therefore, after a cost-benefit analysis, our plan does not seem so costly after all.

8. Sensitivity Analysis

Carbon capture sequestration cost is sensitive when analyzed with respect to varying distances to ocean. Since finding all coal plants in the United States is a near-impossible task, we are forced to use the cost for a 500-meter distance between the coal plant and the ocean. Given the variance in distances the model loses accuracy the farther a coal plant is from 500 meters from the ocean. The cost of 3000-meter injection is unaffected because it is not dependent on any input. Natural gas is also given a set cost and does not suffer from inaccuracy.

The most sensitive of the components is the equation for terrestrial sequestration, as a plethora of costs exists. We chose to use the cost determined by Newell and Stavins in 1999 (See Assumption 10), but there exist 36 other potential costs for the terrestrial part of our plan. Running all of these values through the equation to determine total cost of terrestrial sequestration yields linear results, but two values are significantly distant from the majority of the results, showing that the model can lose accuracy with extreme values for inputs.



9. Strengths and Weaknesses of Model

Strengths

- Model's handling of coal carbon dioxide capture and storage can actually be realistically implemented.
- All data is taken from highly qualified, credible sources.
- Model can be updated given future data.
- Model extensions show that carbon neutrality nigh on impossible and lacking feasibility.

Weaknesses

- Terrestrial sub-model was based on pixel counting integration, which inherently can lose some measure of accuracy.
- Coal sub-model assumed the possibility of 100% capture based on possibly inaccurate pixel height count and extrapolation.
- While heavily researched, dependency upon one source (Stavins) for a high percentage of data possible weakens reliability of model.
- Broad range of research provided monetary values from different years that were not adjusted for inflation.

10. Extensions of Model

What if we were to reforest all of the United States except urban areas, or simply all of the United States? Using the same cost and emission data but much greater land areas, we can take a new look at our problem.

Using All Land Except for Urban Areas:

All land area with the exception of urban areas for each reforestation region is as follows:
Black Walnut Regions: 566,700,000 acres
Loblolly Regions: 526,900,000 acres
Ponderosa Regions: 740,800,000 acres

$$C_t = T\left[(\int_0^{155} R_{s1})A_1 + (\int_0^{155} R_{s2})A_2 + (\int_0^{155} R_{s3})A_3 \right]$$

$$= 199.66\left[(257.2936)(740800000) + (134.3675)(526900000) + (151.2651)(566700000)\right] = \$69,306,631,449,300$$

The metric tons of CO_2 sequestered becomes 347,123,266,800 using all land but urban, only solving for 35.07 the accumulated carbon emissions of 989688.95 MMT, more than doubling the solvency but at much more the cost.

Using All Land in the Continental United States

Black Walnut Regions: 592,400,000 acres
Loblolly Regions: 549,700,000 acres
Ponderosa Regions: 751,700,000 acres

$$C_t = T\left[(\int_0^{155} R_{s1})A_1 + (\int_0^{155} R_{s2})A_2 + (\int_0^{155} R_{s3})A_3 \right]$$

$$= 199.66\left[(257.2936)(751700000) + (134.3675)(549700000) + (151.2651)(592400000)\right] = \$71,254,433,009,900$$

The metric tons of CO_2 solved for becomes 356,878,859,110 using all land. This solves for 36.06% of accumulated emissions, a slight improvement from our previous scenario, yet still far from being effective.

Clearly, the United States cannot neutralize its emissions just by increasing consumption alone, even with an infinite amount of capital. However, our model does not account for the possibility of technological breakthroughs in the future.

11. Summary to Congress

November 9, 2008

Dear Congress,

The impacts of global warming can no longer be ignored. With 2005 as a record year for hurricanes and tropical storms due to the warming of ocean waters, the United States is now beginning to feel the repercussions of global warming along with the rest of the world. This is fitting, for we are currently largest contributor of carbon dioxide, which is the root of the problem. We can promise to cut emissions, but that only provides an excuse continue this lifestyle of pollution. To ensure the best possible Earth for our posterity, the United States must embark upon a campaign to increase carbon dioxide consumption.

Since the United States' emission of carbon dioxide is so severe, extreme measures will be necessary in order to approach this problem. We propose executing a massive reforestation program, replacing trees from said land with trees that effectively sink carbon. This should be supplemented with a plan for retrofitting existing coal and natural-gas-fired plants, as well as equipping them with technology and infrastructure to deposit carbon dioxide 3000 meters into the ocean.

According to our model, the plan will increase the amount of carbon consumed in the United States and neutralize carbon emissions from electricity production through coal and natural gas in a safe and cost-efficient manner. For the start up cost of about 200 billion dollars, the United States can neutralize the emissions of a majority of its power plants. If this Congress was willing to expend 700 billion dollars to save Wall Street, surely it would appropriate about 30% of that amount to save our planet. For the reforestation, our model is too massive to implement realistically, but it shows that the plan would be removing carbon dioxide at a rate of about $197.67 per metric ton when implemented on a smaller scale. This is a reasonable price to pay for the planet which has given us so much.

If no action is taken, the United States will continue to perpetuate this cycle of environmental destruction. The results could be catastrophic. Any hope of reversing these negative trends requires immediate action. Therefore, we strongly urge Congress to implement the retrofitting of carbon capture technology portion of our plan and an adaptation of reforestation.

Sincerely,

The National Committee on Carbon Sequestration

12. Appendices

Appendix I

Total Emissions

	Electricity	Coal	Natural gas	Petroleum
Residential				
2006	865.58	0.59	237.27	100.32
2030	1,079.09	0.72	282.48	88.46
Commercial				
2006	832.47	6.20	154.55	52.58
2030	1,216.18	7.91	200.69	49.36
Industrial				
2006	641.72	189.46	399.23	421.37
2030	647.18	216.86	432.76	436.05
Transportation				
2006	4.08	0.00	32.52	1,952.35
2030	5.47	0.00	42.79	2,145.01
Electricity generation				
2006	0.00	1,937.87	339.53	54.56
2030	0.00	2,615.13	272.19	48.30
	total emissions sequestered by trees			
		5944.56		

Total carbon dioxide emissions	
2006	5,890
2007	5,977
2008	5,983
2009	5,978
2010	6,011
2011	6,087
2012	6,144
2013	6,154
2014	6,187
2015	6,226
2016	6,272
2017	6,308
2018	6,350
2019	6,368
2020	6,384
2021	6,416
2022	6,438
2023	6,483
2024	6,531
2025	6,571
2026	6,622
2027	6,678
2028	6,735
2029	6,783
2030	6,851

Appendix II – Cost of carbon sinks

Table 2: Forest Carbon Sink Studies that Estimate Costs of Carbon Sequestration

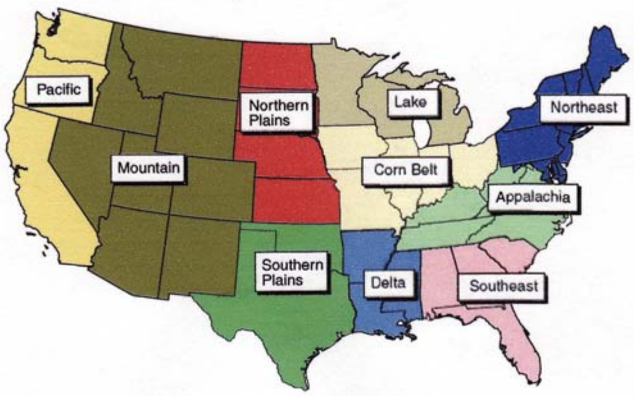
Forest carbon sink studies	Total carbon (Mt)	Total area (mil ha)	Cost ($/ha)[a]	Cost ($US/tC)[a]
Adams et al. (1993)	350.00000	58.999056	442.28	73.20
Adams et al. (1999)	2023.07692	145.596613	401.52	29.16
Andrasko, Heaton & Winnett (1991)	806.00000	6.716000	1101.94	8.88
Baral & Guha (2004)	316.75000	1.000000	18602.34	63.30
Benitez & Obersteiner (2003)	2503.33333	237.000000	698.81	66.16
Benitez et al. (2006)	8183.66667	2975.000000	354.11	128.73
Boscolo & Buongiorno (1997)	0.00123	0.000050	2911.45	118.03
Boscolo, Buongiorno & Panayotou (1997)	0.00140	0.000050	1371.29	49.13
Brown, Cabarle & Livernash (1997)	8.90000	0.560801	10.29	1.84
Cacho, Hean & Wise (2003)	0.00010	0.000001	773.64	7.79
Callaway & McCarl (1996)	119.31818	29.624646	143.39	34.09
Darmstadter & Plantinga (1991)	155.97333	0.523667	1056.39	3.30
Dixon et al. (1993)	5.98500	0.029840	180.72	4.73
Dixon et al. (1994)	0.81357	0.010000	27.91	27.91
Dudek & Leblanc (1990)	1721.91805	4.896803	1562.43	4.44
Dutschke (2000)	1.08088	0.135750	363.02	32.43
FAO (2004)	1.37713	0.094178	171.12	77.11
Fearnside (1995)	0.00002	0.000001	2004.77	89.78
Healey et al. (2000)	0.01578	0.000406	2772.95	71.34
Hoen & Solberg (1994)	0.77847	0.575000	2407.49	1778.25
Houghton, Unruh & Lefebvre (1991)	1277.77780	27.722223	447.48	12.95
Huang & Kronrad (2001)	0.05625	0.001000	838.78	44.63
Krcmar & van Kooten (2003)	3.02600	1.236390	370.14	151.23
Lasco et al. (2002)	2.59761	0.020438	610.38	4.81
Lashof & Tirpak (1989)	834.58333	138.650000	83.00	13.76
Makundi & Okiting'ati (1995)	30.27400	0.186380	324.90	2.00
Masera et al. (1995)	150.66771	1.295429	3038.74	48.63
McCarl & Callaway (1995)	243.88372	47.390233	383.74	72.36
McCarney, Armstrong & Adamowicz (2006)	50.00000	0.888713	142.71	11.04
Moulton & Richards (1990)	472.68069	1.988651	5227.11	26.77
Moura Costa et al. (1999)	11.60644	0.210933	202.93	4.37
New York State (1991)	0.50250	0.804341	17.33	29.51
Newell & Stavins (1999)	7.66417	2.074701	699.79	181.13
Nordhaus (1991)	3550.00000	85.000000	4144.36	115.75
Olschewski & Benitez (2005)	18.05400	0.102000	2576.21	14.55
Parks & Hardie (1995)	29.96400	6.576285	967.26	260.29
Plantinga & Mauldin (2001)	41.54904	0.275678	5457.40	36.28

Appendix III

Land Regions

Figure 3

USDA farm production regions



Source: Economic Research Service, USDA.

land constitutes a relatively high share of land in the Lake States and Pacific regions where the topography and precipitation patterns are also conducive to growing trees. The Northeast and Southeast have the highest shares of urban land, while the Lake States, Corn Belt, Appalachian, and Pacific regions also have urban shares above the Nation's average.

Region	Forest Use	Special/Misc Use	Total Land
Northeast	65.5	16.8	82.3
Lake States	49	21.4	70.4
Corn Belt	31.3	16.5	47.8
Northern Plains	4.3	15.9	20.2
Sub-Total	150.1	70.6	220.7
Appalachian	71.5	13.4	84.9
Southeast	73.7	17.8	91.5
Delta States	50.7	11	61.7
Southern Plains	18	16.7	34.7
Sub-Total	213.9	58.9	272.8
Mountain	116.8	78.3	195.1
Pacific	78.3	42.1	120.4
Sub-Total	195.1	120.4	315.5
TOTAL:	559.1	249.9	809

*Major use of land by region 2002

*Data in millions of acres

Table 4

Major uses of land by region, 2002

Region [1]	Cropland [2]		Grassland pasture and range [3]		Forest-use land [4]		Special uses and misc. other land		Urban area		Total land area [5]	
	Mil. acres	*Pct.*	*Mil. acres*	*Pct.*	*Mil. acres*	*Pct.*	*Mil. acres*	*Pct.*	*Mil. acres*	*Pct.*	*Mil. acres*	*Pct.*
Northeast	13.7	12.3	3.0	2.7	65.5	58.9	16.8	15.1	12.3	11.1	111.4	100
Lake States	42.1	34.5	5.4	4.4	49.0	40.2	21.4	17.5	4.2	3.4	122.1	100
Corn Belt	95.7	58.2	13.1	7.9	31.3	19.0	16.5	10.0	8.0	4.9	164.6	100
Northern Plains	102.0	52.5	71.0	36.6	4.3	2.2	15.9	8.2	1.0	0.5	194.3	100
Appalachian	26.0	21.0	6.3	5.1	71.5	57.8	13.4	10.8	6.5	5.3	123.7	100
Southeast	14.8	12.0	8.3	6.7	73.7	59.7	17.8	14.5	8.7	7.1	123.3	100
Delta States	21.0	23.1	6.2	6.8	50.7	55.5	11.0	12.1	2.3	2.5	91.2	100
Southern Plains	55.7	26.3	115.8	54.7	18.0	8.5	16.7	7.9	5.3	2.5	211.5	100
Mountain	46.3	8.4	302.8	55.3	116.8	21.3	78.3	14.3	3.7	0.7	547.9	100
Pacific	23.9	11.7	52.3	25.7	78.3	38.4	42.1	20.7	7.1	3.5	203.8	100
48 States [4]	441.3	23.3	584.2	30.8	559.1	29.5	250.0	13.2	59.2	3.1	1,893.8	100
Alaska	0.1	0.0	1.3	0.4	90.5	24.7	274.0	74.9	0.2	0.0	366.0	100
Hawaii	0.2	4.5	1.0	24.4	1.6	37.8	1.1	27.8	0.2	5.5	4.1	100
United States [4]	441.6	19.5	586.5	25.9	651.2	28.8	525.1	23.3	59.6	2.6	2,264.0	100

[1] See fig. 3 for a map of the Farm Production Regions used in this report.
[2] Includes cropland used for crops, cropland used only for pasture, and idle cropland.
[3] Open permanent pasture and range, both in farms and not in farms, excluding cropland pasture.
[4] Includes forests grazed but excludes an estimated 98 million forest acres in parks and other special uses of land.
[5] Distribution of land uses and percentages may not add to totals due to rounding.

Sources: DOI/BLM, 2003; DOT/BTS, 2004; DOT/FAA, 2002; DOT/FHWA, 2002; DOT/FRA, 2004; USDA/FS 1989, 1998; DOI/FWS, 2001; GSA, 2001; GDT, 2000; HUD/BOC, 1992, 2002, 2003; USDA/NASS, 2004a, 2004b, 2005; DOI/NPS, 2002; USDA/NRCS, 2000, 2004a; and WI, 2002.

Appendix IV

Algorithms

1.Terrestrial Sequestration of Carbon Dioxide

1.1 Data Gathering using Pixel Integration

1.1.1 Pixel count scale generation

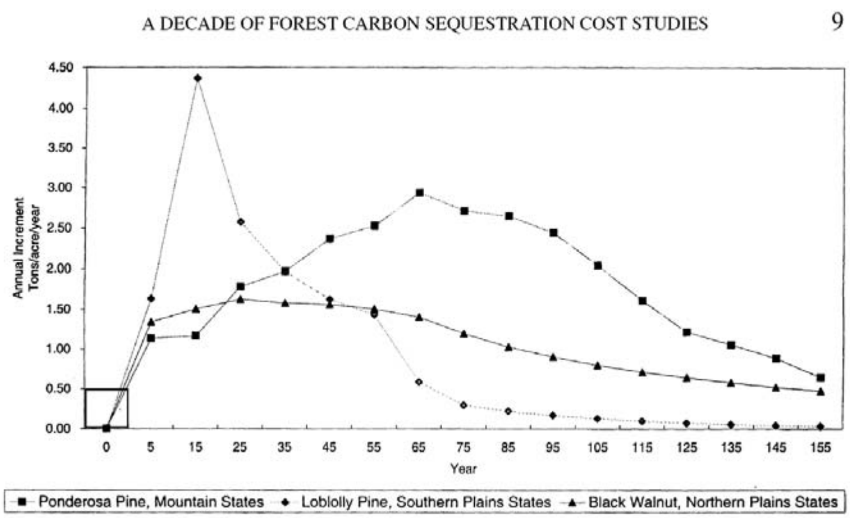


Figure 1. Carbon sequestration rates in the United States for three region/species combinations.

Since actual data for this graph was not included with the article, pixel integration was necessary to calculate how effective terrestrial sequestration would be (in tons of CO_2 mitigated per acre over155 years). We could find this because integration would yield tons/acre/year * year, which simplifies to tons per acre. To gain a measure of scale we measured the pixels contained in a rectangular section of the graph, shown above, that would integrate to 2.5 tons CO_2 per acre for the first data point and 5 tons CO_2 per acre for all others. The reason for the difference for the first data point is that the scale is different for that data point. The rectangle contained 3127 pixels.

3127 pixels = 2.5 tons/acre (first point)

Therefore 1250.8 pixels = 1 ton/acre.

3127 pixels = 5tons/acre (all other points)

Therefore 625.4 pixels = 1 ton/acre.

1.1.2 Adobe Photoshop Pixel Count

Next we loaded the image into Adobe Photoshop 6 and proceeded to extract six images from it. Select ‘Filter’, then ‘Extract’. Check the box labeled ‘Smart Highlighting’, and set brush size to 2. Zoom in approximately 500%, select the Edge tool, and then highlight the edge of the area under the curve in green, (the default edge color), following the center of the lines between points. When finished, select the Fill tool and fill the area you want with blue, (the default fill color). Click OK. This will yield all of the pixels necessary to calculate the effectiveness of terrestrial sequestration. Now press CTRL+A to select the entire image, and then double click the image. Now select ‘Image’, then ‘Histogram’. The Histogram dialog will give a pixel count for the area you selected earlier. Repeat this process 5 times to get all of the data required.

1.1.3 Pictures from Integration Process and Resultant Values

	Pixels	Tons per Acre	Metric Tons per Acre	Total Metric Tons per acre
Loblolly Pine-1st	5170	4.13335465302	3.74971626623	
Loblolly Pine-Rest	90046	143.981451871	130.61777598	134.367492246
Black Walnut-1st	3906	3.1228014071	2.83295778257	
Black Walnut-Rest	102327	163.61848417	148.432192021	151.265149804
Ponderosa Pine-1st	3363	2.68867924528	2.43912878208	
Ponderosa Pine-Rest	175693	280.929005437	254.854506755	257.293635537

2. Electricity Retrofitting and Ocean Sequestration

2.1 Coal Retrofitting Cost

2.1.1 Pixel Length Used to Get Data

We also encountered a bar graph of cost per Metric Ton of CO_2 removed from coal production that lacked data, so data had to be approximated using pixel counting. Using the GNU Image Manipulation Program, we found that 88 pixels corresponded to $20/Metric Ton. Measure the height of each bar in pixels. Then divide by 88 pixels and multiply by $20/Metric Ton to get the cost in dollars per Metric Ton value for each percentage of capture.

2.1.2 Regress Data to Extrapolate 100%

%	Pixel Height	Cost per Metric Ton in dollars
90	394	89.55
70	425	96.59
50	440	100
30	499	113.41

We entered the values in the '%' column into '`list1`' of a TI-89 Titanium Edition graphing calculator and the values in the 'Cost per Metric Ton in dollars' column into '`list2`'. The article that the graph was found in stated that the relationship between percentage and cost per Metric Ton in dollars is linear, so we did a linear regression of these 4 values, and then calculated the cost of capturing 100% of the Carbon dioxide produced by coal electricity generation, using the following method.

From the '`HOME`' screen:

```
Press 'APPS'.
Select 'Stats/List Editor'.
Press 'ENTER'.
Press 'F4'.
Select 'Regressions'.
Press 'ENTER'.
Press '1' (Choosing LinReg(a+bx)).
Enter 'list1' into the X List field and 'list2' into the Y List
field.
Set the 'Store RegEqn to:' field to y1(x).
Press 'ENTER'.
Press 'HOME'.
Type in 'y1(100)'.
Press 'ENTER'.
```

The value we received was $84.89 per Metric Ton of CO_2 captured from coal electricity generation. The regression equation received was y1=122.38636363636-0.375x

Works Cited

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