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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: 2157
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.

Our group's task was to develop a model that accurately predicts the effect of carbon sequestration on annual American carbon emissions. Research turned up two of the most effective methods of sequestration: Carbon Capture Systems, which "catch" the carbon emitted by plants and factories and store it in various vessels or cycles, and natural sequestration, which refers to the strategic planting of certain trees, grasses, and algae to absorb the carbon in the atmosphere. A complete model of carbon emissions will take both of these methods into account.

We approached the problem first by assuming that the gross amount of carbon emitted each year by the U.S. remained constant. This allowed us to concentrate solely on methods of sequestration in our equation. We then defined functions to account for the time-dependent factors of the model, such as the time that it would take for a factory to implement CCS or for a farmer to grow trees. The model was found to decrease carbon emissions for twenty years, after which they would level off at about 2,000 million metric tons a year.

After defining the functions necessary for our model, we examined its economic feasibility. Reasonable assumptions of area, efficiency, and cost revealed that the model would be fairly expensive, but would easily fit within the United States Federal Budget.

Both economically feasible and effective at reducing carbon emissions, our model is highly promising and reveals the potential for sequestration as a method of curbing greenhouse gas accumulation. However, it does not appear able to achieve complete carbon neutrality, which would require curbing carbon emissions as well.

A Mathematical Model of Carbon Emissions In the United States After Implementation of Sequestration Systems

Team 2157

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Problem Restatement

Our team chose to model Problem B. One of the greatest problems facing the United States is that of carbon pollution. Carbon levels can be managed either by reducing the amount that is emitted or by "sequestering" carbon which is already present in the atmosphere. Our objective is to identify effective methods of sequestration and their impact on carbon levels. Each sequestration method will be modeled in terms of both environmental and economic impact. The overall objective is to determine the effectiveness of sequestration methods in the modern United States economic environment and whether carbon neutrality by carbon sequestration alone is feasible.

Assumptions and Justifications

1. The level of gross CO_2 emissions is constant and will remain at its current level of 5,983 million metric tons per year.[1] ([Online], 2008)
    a. This assumption is twofold. First, we must assume that emissions will not rise above the current cap. This is a reasonable assumption considering that many policies to reduce carbon emissions are currently being implemented across the United States. This assumption is given in the prompt. Secondly, we will assume that emissions will also not decrease. Such an assumption is justified by our concentration on sequestration rather than reduction.
2. Industrial and commercial sectors will be willing and able to implement carbon capture and storage systems
    a. Given the likelihood of national/international carbon taxes or carbon-trading systems, economic advantages necessitating carbon reduction systems will likely form over the studied time period. While high carbon emissions may be expensive for companies to mitigate, taxes and mandates can make greener solutions more fiscally attractive.
    b. The EPA is no longer allowed to issue permits for construction of power plants without explicit limits and expectations for carbon dioxide emissions.[2] ([Online], 2008) Such limitations encourage the use of carbon capture and storage methods.
3. The distribution of gaseous carbon in the atmosphere is constant across all regions of the United States.
    a. Chemical properties and uneven distribution of populations mean that the amount of carbon may be different at different locations across America. However, given

[1] Energy Information Administration, (2008, may). Emissions of greenhouse in the U.S. 2006. *EIA-Official Energy Statistics from the U.S. Government*, Retrieved November 16, 2008, from http://www.eia.doe.gov/oiaf/1605/flash/flash.html.

[2] Hebert, H.J. Utah coal plant permit blocked by EPA panel. (2008, November 13). *Associated Press*, from http://www.google.com/hostednews/ap/article/ALeqM5gSt_gge-bueZU2rGVTx1SPZzbkAwD94ECPU04.

the highly random nature of this phenomenon, it will be more useful to assume an "uniform distribution" model, in which the levels are spread out similarly everywhere.

4. In the natural carbon sequestration model, the maximum amount of CO_2 taken out of the air each year by plants remains constant.
    a. As the level of carbon in the atmosphere decreases, plants are less likely to absorb the same amount. However, given an even distribution of carbon dioxide over the United States (as stated in assumption 3), it is reasonable to assume that an appreciable amount will exist for plants to use.
5. We are only concerned with reducing an amount of CO_2 equal to that of the amount produced by the USA.
    a. The CO_2 emitted within the United States obviously does not remain in national airspace. That being said, the model asks for United States emission neutrality; to achieve such a state, we must sequester as much CO_2 as we produce. The origin of the carbon dioxide is irrelevant.
6. The carbon capture systems at factories and power plants can capture 80% of emissions.
    a. Current studies indicate that existing CCS technology can effectively reduce emission rates by 80-95%.[3] (UNEP, 2005)
7. The technology for carbon sequestration will not become more efficient in the time period of our model.
    a. Plotting the projected path of a technology is a difficult task. We cannot be sure of the innovations that will arise over the course of our projected model; hence, we will assume that the technology for Carbon Capture and Storage (CCS) systems will remain at its current performance level.
8. Carbon reduction systems will be adopted in the same quantities at the same times across several different sectors (e.g. power plants and manufacturing).
    a. Federal economic conditions, which have been assumed to be the main motivator in implementing carbon reduction systems, are generally not isolated to single sectors. The conditions of the market affect manufacturing plants and energy producers in, if not identical, at least comparable ways. Therefore, it is reasonable to assume that these different sectors will construct carbon storage and utilization methods at the same rate.
9. Switchgrass will immediately reach its maximum potential for carbon dioxide absorption, without any time necessary for growth.
    a. The main plan for implementation of switchgrass sequestration, outlined below, involves letting the side tracts of federal highways go un-mowed. Since switchgrass grows quickly and will require little to no attention, this is not an

[3] Intergovernmental Panel on Climate Change, (2005). *Carbon Dioxide Capture and Storage*. Cambridge, England: Cambridge University Press.

entirely inaccurate assumption; as the period for growth of switchgrass is at most two years, only a small modeling error would be created.

Solution

We realize that the problem cannot be completely solved by a single sequestration method. Therefore we believe in using a variety of sequestration techniques. These all fall within two general categories: Carbon Capture and Storage systems and natural carbon sequestration. Both of these systems offer unique benefits, while also involving separate cost and liability concerns.

A Review of the Methods of Carbon Capture and Storage

1. Carbon Capture and Storage (CCS) systems

The main objective of carbon capture systems is to capture carbon where it is produced the most heavily: factories and power plants. The captured carbon dioxide can either be stored in a carbon sink or be put to use in some other way. The two uses that we will include in our model are Enhanced Coal Bed Methane Recovery and algae-to-biofuel systems.

Enhanced Coal Bed Methane Recovery (ECBM) is a method for utilizing carbon dioxide to obtain other fuels while sequestering it in a sustainable manner. Coal is an extremely porous material: thousands of tiny holes permeate its surface. These holes are filled with a variety of gases; one of which is methane, a useful natural fuel. However, in order to utilize these gases, the methane must somehow be forced out of its porous abodes. Carbon dioxide provides a particularly effective harvesting method. When the gas is pumped into subterranean coal beds, it displaces the methane, forcing it out of the micropores. A harvester can then extract this methane.

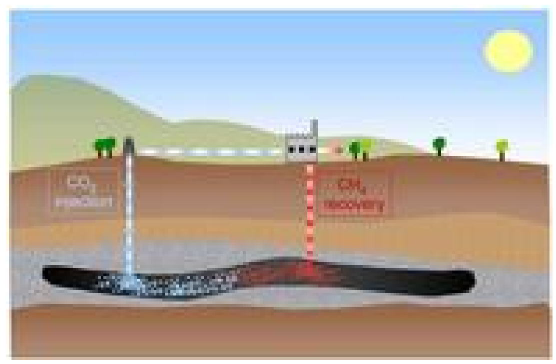

Figure 1. A diagram of a sample ECBM system. Carbon dioxide is pumped into the coal bed, forcing out methane gas which is harvested on the surface.

ECBM is a profitable Carbon Capture and Storage system in that it both sequesters carbon dioxide and produces a marketable fuel. However, several problems have arisen in preliminary investigations of the process. First, some believe it to be economically unfeasible. Mazzotti found that, while ECBM has higher yields than traditional reservoir pressure-depletion (in which the coal bed is compressed and degassed), it is still limited by economic factors involving carbon dioxide emissions and collection[4]. (Mazzotti, 2006) However, this problem is easily addressed by assumption two, which states that economic measures would ensure that corporations would

[4] Mazzotti, Marco (2006, August 31). Enhanced coal bed methane recovery. Retrieved November 16, 2008, from ETH Zurich Web site: http://www.ipe.ethz.ch/laboratories/spl/research/adsorption/project03.

pursue carbon reduction methods, presumably including ECBM. The second is that, in order to implement this method on a large scale, a large infrastructure of methane harvesters, $C0_2$ transporters, and carbon dioxide pumps is required. However, given the proper economic incentives, this infrastructure could be constructed with relative ease.

Another possible method of CCS involves algae biofuel cycles. Several biofuel production plants have begun creating lakes in which to grow algae with emitted CO_2. Carbon is captured and stored using traditional CCS methods and then pumped into the lakes. Though normally harmful to marine life, CO_2 facilitates algae growth. The algae is then harvested continuously and used in a variety of biofuels and animal products.[5] (Hebert, 2008)

Algae-to-biofuel programs are a highly effective form of CCS. They provide an economic motivation (the goods and biofuels produced by harvesting the algae) and a cycle in which to continuously store CO_2. Possible problems include concerns about the fate of CO_2 in the long run and the issues with switching the production models of major industrial centers. Eventually, factories will close down or move and the CO_2 trapped in the algae-to-biofuel cycle will be released into the atmosphere. However, such emissions are minimal over time when compared to overall captures. Also, factories must adjust their day-to-day operations to include carbon pumping and algae harvesting, which could prove to be an expensive process. Assumption Two, however, ensures that economic measures will counteract this potential issue.

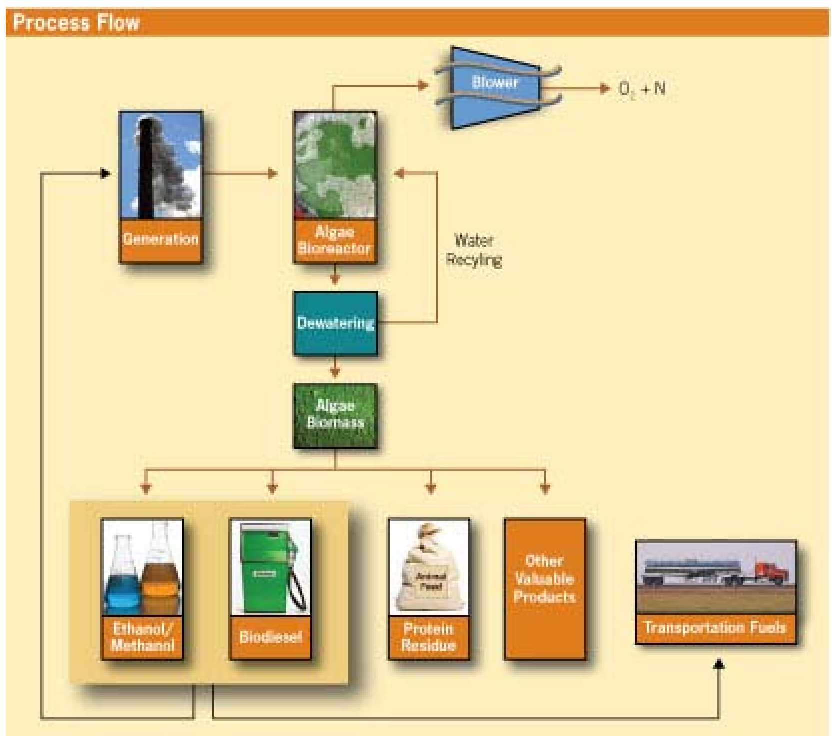

Figure 2. A diagram of the process of algae-to-biofuel conversion. Carbon from burning algae is used to grow more algae, which can then be used to produce a number of goods.

These two systems are uniquely attractive due to their differing yet significant returns on the initial investment. Some facilities will not be able to use the captured gases in such a way. Instead they will store the gas underground in sinks. If the location does not allow for a carbon dioxide sink, the gas can be piped to a nearby

[5] Hebert, H.J. Utah coal plant permit blocked by EPA panel. (2008, November 13). *Associated Press*, from http://www.google.com/hostednews/ap/article/ALeqM5gSt_gge-bueZU2rGVTx1SPZzbkAwD94ECPU04.

reservoir for storage. These basins can store the gas indefinitely and effectively. One recent study in Texas found a basin that could hold 33 years of America's total greenhouse gases.[6] ([Online] 2007) Basins can be anything from empty oil well, spent mines, and porous rock formations to caverns.[7] ([Online] 2005) Given the abundance of sites such as these, carbon storage is not considered a sizeable problem in our model.

2. Natural Sequestration Methods

Already commonly-grown plants can serve as effective sequestration tools if implemented correctly. Plants utilize CO_2 in photosynthesis to obtain energy. They are therefore the most traditional and well known countermeasures to rising greenhouse gas emissions. With the destruction of rainforests and expanding industrial and agrarian areas, it is especially important at present to explore options for aggressive anti-carbon planting. There are several different kinds of natural sequestration methods that all essentially revolve around the principle of using plants to decrease atmospheric carbon dioxide.

The plants most generally used for sequestration are algae, trees, and switchgrass. Algae is grown in pools or open seas. It is highly effective, removing an average of 202 metric tons of atmospheric carbon per acre per year. (See Appendix A for calculations). Trees can be further split into two categories: forestland trees and farmland trees. Forestland trees are those that normally come to mind: trees growing in densely packed woodlands. Farmland trees are those planted on agrarian land to break the wind and prevent erosion. The latter is the most important to our model, given the obvious incentives to plant trees on farmland. These groups remove about 786 metric tons per acre per year. Switchgrass, or grassland in general, can remove 525 metric tons per acre.[8] (Dept. of Energy, 1999) These estimates are conservative and assume relatively low levels of carbon absorption, meaning that the model suggests a positive impact from natural sequestration.

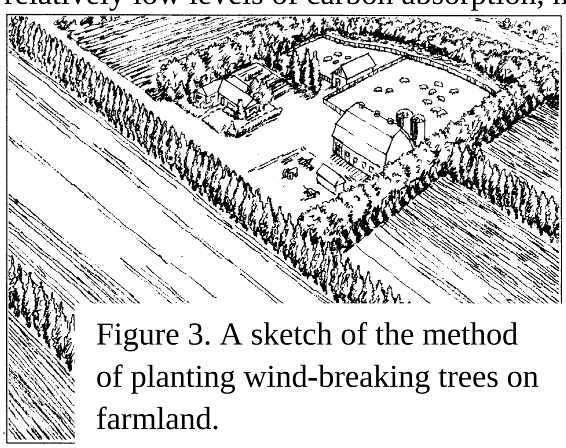

Figure 3. A sketch of the method of planting wind-breaking trees on farmland.

CO_2 levels can easily be reduced through simple aggressive planting. Giving land to trees and grass greatly decreases the amount of atmospheric carbon and helps to overcome emissions. It is also cheap and mostly uninvolved with corporations, meaning that implementation could be quick and easy. Clearly, this is a tenable method and has a place in our model.

[6] University of Texas, Bureau of economic geology receives $38 million for first large-scale U.S. test storing carbon dioxide underground. (2007, October 24). *Jackson School of Geosciences News Releases*

[7] Socolow, R.H. (2008, July). Can we bury global warming?. *Scientific American*, 42.

[8] USDA, (2000, December 12). Working trees for carbon cycle balance. Retrieved November 16, 2008, from NAC Web site: http://www.unl.edu/nac/brochures/wtcarbon/.

One commonly voiced concern is that natural sequestration would require huge tracts of land and thus would cut profits from other methods of land use. The federal government alone, though, owns over a million acres of empty land on the sides of federal highways. The government owns at least 25 feet of land on either side of each highway for its entire length. This figures out to 978,145.455 acres of land and, conservatively, 488,000 acres of usable land.[9] (FHWA, 2003) This land can be neglected (i.e. not mowed) for a short period of time to stimulate growth of grassland and provide a large amount of carbon-reducing land. Further, let us project that only 1% of the arable land in the United States can be devoted to algae growth. Agriculturists would be willing to sacrifice this land due to the economic advantages granted by selling the harvested algae and the pressures outlined in assumption two. Such a small segment of land would represent 4,077,392.82 acres, more than enough to make the algae contribution effective.[10] (CIA, 2008) Clearly, the contention that providing land will be insurmountable is unfounded.

Mathematics

Our model represents net emissions per year; that is, the quantity by which the total amount of CO_2 in the atmosphere changes with each year. We assume the gross amount of carbon emitted each year is held constant at 5,983 million metric tons and subtract from this the amount of carbon removed through CCS and natural sequestration. In order to account for the rate at which each sector implements CCS and the efficacy of these methods at neutralizing carbon emissions, we define an additional function $V(t)$, a real valued function with an upper bound at one and inversely proportional to the efficiency of each method (percentage of carbon scrubbed) multiplied by the percentage of facilities that use the methods. $E(t)$ resembles a logistic function: it approaches a lower bound of about 2,000 million metric tons per year, at which point it will remain constant. The exact functions and variables are explicated below.

$$E(t) = \text{Net carbon dioxide emissions in millions of metric tons } t \text{ years after 2008}$$

$$E(0) = \ 5983 \text{ million metric tons}$$

5983 million metric tons of carbon dioxide are projected to have been emitted in 2007 (exact figures are not yet available).

$$E(t) = \ FV(t) + T + R - (AC(t) + S + WG(t)\ )$$

$$V(t) = 1 - \text{efficiency of CCS} * \% \text{ of facilities which use CCS}$$

[9] Federal Highway Administration. (2004). *National highway road system length* (Table HM-40).
[10] CIA, (2008). United States data. Retrieved November 16, 2008, from The World Factbook Web Site: https://www.cia.gov/library/publications/the-world-factbook/geos/us.html

$$F = \text{carbon released by industrial and commercial sectors yearly}$$
$$= 2735 \text{ million metric tons per year}$$

2,735 million metric tons of carbon dioxide were released by these sectors in 2007. This is given as a starting point. $V(t)$ then acts as a modifier on this constant emissions rate: as CCS becomes more popular and effective, the net emissions released by these sectors decreases, which is effectively represented by our model. The efficiency of CCS systems is assumed to be constant at 80%. To determine the percentage of facilities which will be using CCS in a given year we decided to use a logistical population growth differential equation.

$$n' = kn(C - n)$$

$$n = \frac{c}{de^{-ckt} + 1}$$

We believe that it will take approximately 15 years for half of facilities to implement CCS. We also assumed that 1% of buildings used some sort of CCS in 2008. Using these values we were able to solve the IVP.

$$n(0) = .01 \quad n(15) = .5 \quad n = \frac{1}{99e^{-1*(.306)t} + 1}$$

with t in years (after 2008).

$$T = 2007 \text{ amount of CO2 produced by transportation sectors yearly}$$
$$= 2006 \text{ thousand million metric tons per year}$$

$$R = 2007 \text{ amount of CO2 produced by residential sectors yearly}$$
$$= 1242 \text{ thousand million metric tons per year}$$

CCS cannot feasibly be applied to transportation or residential situations. Therefore, they are not given growth coefficients. Though the emissions in these sections could be decreased, that is outside of the scope of our model and addressed in assumption one.

$$A = A_r A_a = \text{Amount of carbon consumed by algae}$$

$$S = S_r S_a = \text{Amount of carbon consumed by switchgrass grown on highway}$$

$$W = W_r W_a = \text{Amount of carbon consumed by agroforestry}$$

$$A = (202)(4{,}077{,}392.82) = 823.63 \text{ million metric tons}$$

$$S = (340.2)(978{,}145.455) = 332.76 \text{ million metric tons}$$

$$W = (785.9)(237{,}715.85) = 186.84 \text{ million metric tons}$$

(all emission values)[11]

These three values will vary with each year as these systems of natural sequestration are implemented more widely and efficiently. The values can be found by multiplying the rate of carbon dioxide carbon consumption of each method, X_r, by the area covered by each method, X_a . The efficiencies of each method were addressed earlier in the paper.

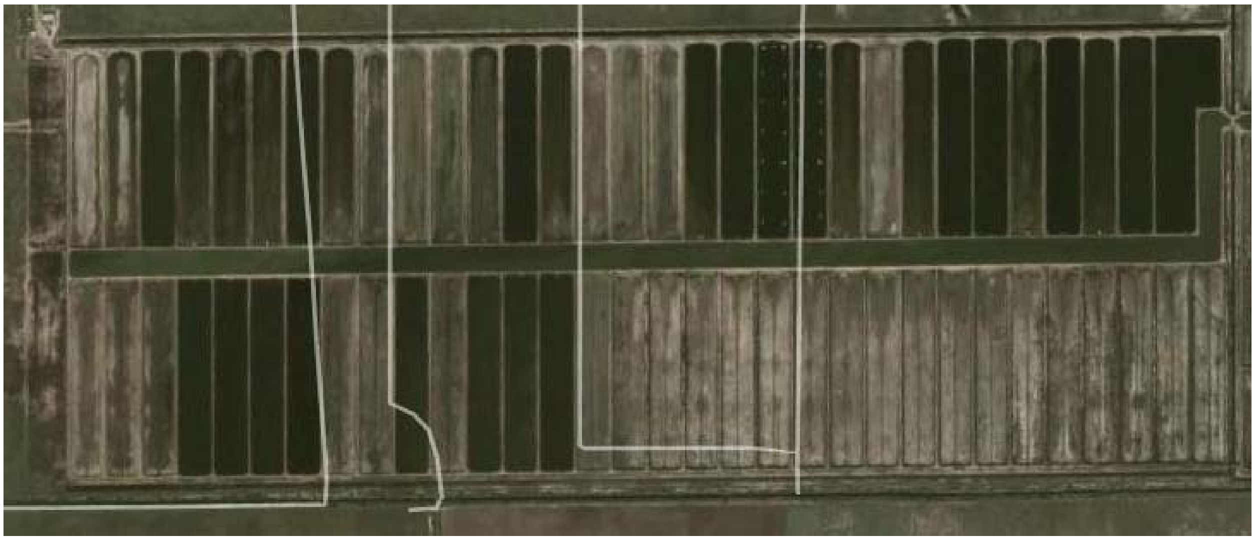

Figure 4. A satellite picture of an algae farm. Several algae pools are left empty to harvest the biomass, while others can be seen to be full.

To determine the amount of CO2 land that could be used for algae farming, we first needed to account for the amount of land that would be able to support algae. To begin, we planned on 1% of arable land in the United States being dedicated to algae at full implementation. There are 9,161,923 square kilometers of land in the United States, 18.01% of which is arable. This means that there are 16,500,623,323 square meters of arable land in the United States; thus, there are 4,077,392.82 acres available for algae

Figure 5. Harvested switchgrass, ready for testing or biofuel production. The relative length of full-grown grass is displayed.

[11] Energy Information Administration, (2008, may). Emissions of greenhouse in the U.S. 2006. *EIA-Official Energy Statistics from the U.S. Government*, Retrieved November 16, 2008, from http://www.eia.doe.gov/oiaf/1605/flash/flash.html.

production.[12] (CIA, 2008)

The switchgrass area figures come from a planned future use of Federal highways. On each highway, we could plant switchgrass on a 25 foot wide swatch on each side. In the United States, there are 161,394 miles of federal highway. That results in 42,608,016,000 square feet of federal highway land available. If only 50% of such land was suitable for switchgrass plantings, there are 489,072.727 acres of national land that prairie grass carbon elimination could be implemented on.[13] (FHWA,2008) Finally, it was assumed that 5% of farm land could be used to plant wind-breaking trees. This came out to 237,715.85 acres (USDE, 1999).[14]

Two functions were defined to represent the rate of growth of *W* and *A*. (Switchgrass is implemented instantly, as addressed in assumption nine). The function *G*(*t*) was used as the growth coefficient of trees.

$$G(t) = \frac{2}{\pi}\tan^{-1}\left(\left(\frac{\frac{t}{10}}{\tan\left(\frac{.99\pi}{2}\right) - \tan\left(\frac{.3\pi}{2}\right)}\right) + \tan\left(\frac{.3\pi}{2}\right)\right)$$

To obtain this equation, we first identified the type of function that would be best suited to model the growth of the ability of trees to absorb carbon dioxide. When a tree is young, it absorbs little carbon dioxide but grows quickly. As it reaches maturity, its growth slows and begins to approach a maximum size. Maturity was defined to be 10 years into growth; even if the tree had not finished growing by this point, it would be absorbing around its maximum amount of carbon dioxide. At this point the tree would be using approximately 100% of its potential for absorbing carbon dioxide ($G(t)=1$). We therefore wanted a function that was greater than zero for $t > 0$ and always increasing, approaching an upper limit of one at $t = 10$. Inverse tangent was identified as a function with a shape analogous to what was required. Since $\lim_{t\to\infty} \tan^{-1} t = \frac{\pi}{2}$, the function must first be multiplied by $\frac{2}{\pi}$ to obtain our desired limit of 1. Further, the function must reach this limit at 10. The other stretches and additions to the arctangent function shift it to the left and up far enough to limit the function at the desired value.

We felt that the growth of the algae would be better approximated by a logistic function, since the algae farms require a greater initial infrastructure build up than the trees. Thus, the function will begin increasing slowly and then increase more quickly. We chose the function

$$C(t) = \frac{1}{99e^{-.919t} + 1}$$

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[12] Ibid.

[13] Federal Highway Administration. (2004). *National highway road system length* (Table HM-40).

[14] USDA, (2000, December 12). Working trees for carbon cycle balance. Retrieved November 16, 2008, from NAC Web site: http://www.unl.edu/nac/brochures/wtcarbon/.

as an appropriate representation of the coefficient of algae growth. By beginning with the general solution of a logistic differential equation and applying similar techniques to those used for the previous function, the modifications necessary were determined and included.

With all of these values placed into the formula, it assumes its final form. The model's graph appears as a gradually decreasing function, reaching a lower bound of about 2,400 million metric tons per year at t = 20 years. This means that our CCS and natural sequestration methods will reduce annual carbon emissions for about 20 years, at which point emissions will be in equilibrium. The function's graph is shown below.

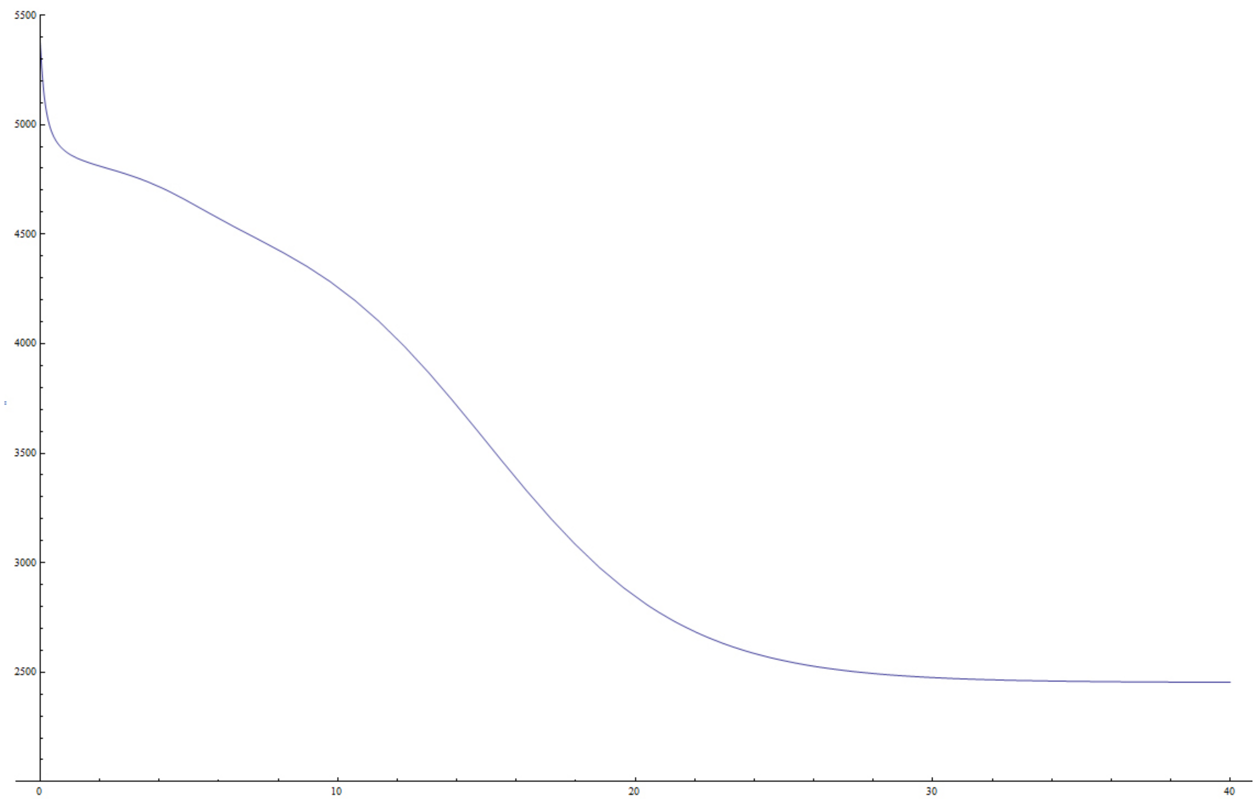

Figure 6. The curve representing our model. Time is in years from 2008 and mass is in millions of metric tons.

Economic Factors

In determining whether or not to go ahead with a carbon sequestration program, the economic feasibility of such a project must be addressed.

The likely largest economic cost is that of retrofitting existing power plants with CCS systems. In evaluating CCS systems, scientists assessed a $7 credit per ton of carbon dioxide as a competitive tax credit. This credit was to be extended over a 10 year period. To calculate, then, the break-even cost of long-term CCS development, we must use this credit as the low-end cost-basis point. With 2.188 million tons of carbon dioxide removed, at the maximum efficacy of CCS-equipped plants, we come to a 10-year cost basis of $153,160,000,000. While a large sum, this amount pales in comparison to the amount of money already spent on the Next-Gen carbon neutral coal plant project, as well as many national defense projects.[15] (National Commission on Energy Policy, 2004)

Secondly, and perhaps equally as important, are the algae pools. Researchers have estimated that algae pools cost approximately $80,000 per hectare.[16] (Briggs, 2004) With approximately 4,077,000 acres dedicated to algae pools, the total cost of installing our requisite numbers of algae pools would come to $132,004,987,000. This sum, while large for a private industry to undertake, pales in comparison to the price of many less valuable government sponsored expenditures.

The cheapest, and yet effective, component of our carbon sequestration program is the nation-wide installation of highway buffer switchgrass. The cost of installing and routinely maintaining switchgrass installations at the side of our national highways comes to a price of approximately $119.11 dollars per acre.[17] (Duffy, 2002) With approximately 489,000 acres at disposal for this project, the total cost comes to around $58,251,000.

In total, the project comes in at around $287 billion, a reasonable value for such a wide-reaching undertaking. The project is therefore economically feasible, at least relative to other elements of the Federal Budget.

Testing The Model

The most efficient testing method for our model would be to run small-scale constructions of each plan. In the instance of Carbon Capture and Storage systems, a complete analysis of a working CCS plant and factory would be required. The ideal manner in which to conduct such a study would be to determine the price increase over a normal plant, the efficacy of the capture and storage system, as well as the effects of the storage medium on the environment.

As for testing the algae ponds, the following statistics need to be quantified: CO_2 absorbed per acre, cost per facility, and miscellaneous additional costs, be they financial or otherwise. The ideal method of testing would be to conduct data analysis of an existing algae facility, verifying the previous experimental results found by existing researchers in the field. To further expand on such findings, it would be useful to develop the facilities outwards and corroborate that the statistics hold true when multiple buildings are constructed.

Switchgrass could be readily tested by running small-scale lab experiments to verify CO2 absorbency, as well as highway test plots to confirm cost structures.

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[15] National Commission on Energy Policy. (2004). *Technical memorandum – National commission on energy policy.*
[16] Briggs , M. (2004, August). Widescale biodiesel production from algae. Retrieved November 17, 2008, from UNH Biodiesel Group Web site: http://www.unh.edu/p2/biodiesel/article_alge.html.
[17] Duffy, M.D. and V.Y. Nanhou. 2002. Costs of producing switchgrass for biomass in southern Iowa. p. 267–275. In: J. Janick and A. Whipkey (eds.), Trends in new crops and new uses. ASHS Press, Alexandria, VA.

Finally, it is essential to take these newfound statistics and extrapolate out to form an updated cost structure and efficacy model. Re-evaluation of the individual component functions, such as the growth rate in the intake of CO2 by trees, would render a more accurate model.

Strengths and Weaknesses of the Model

Strengths	Weaknesses
We take into account a reasonable number of possible solutions for using carbon sequestration which strengthens our model as we do not rely on a single sequestration method.	We assumed that the switchgrass would be effectively implemented instantaneously and that the algae and tree implementation would follow our models; this does not necessarily hold true.
We have created a comprehensive model for emissions of the United State by taking into account the majority of emissions by the various sectors.	All of our data came from others as it was unfeasible to test ourselves. Therefore, we do not know with absolute certainty that the data is reliable and unbiased.
We have generally used more conservative values for our model which will produce the least efficient model given the circumstances and leaves open the possibility to generate a more effective model.	We assumed that all companies would be willing and able to implement CCS. This is an unsure assumption because many may oppose the increased short-term running costs.
We have a wide variety of sources which lend legitimacy to our model as we are able to minimize the effect of biased data that could skew our model.	Long term effects of CCS on the environment are still unknown and could have adverse effects.
The overall implementation of the sequestration systems would be relatively inexpensive compared to our government's national budget and other plans designed to do similar things.	A major weakness is the assumption that the rate of carbon dioxide emissions will remain constant over time. Some argue that carbon dioxide emissions will continue to increase in the United States.

A Letter to Congress

To the Attention of the Members of the United States Congress:

Our country faces a grave crisis in the coming years. Many climatologists claim that global emissions need to begin decreasing by the year 2012 for global climate change to be averted. The United States, despite only comprising a small portion of the world's population, contributes a significant amount of the world's total carbon dioxide emissions. It is our opinion that, as a beacon of liberty and ethical behavior, it is the United States' obligation to do as much as possible to avoid a global climate catastrophe.

In order to limit carbon dioxide emissions, two general strategies can be employed: reducing carbon dioxide emissions or sequestering the carbon emissions already being made. We have chosen to address the latter, developing a comprehensive model and plan that attempts to render the United States a carbon-neutral nation purely by means of carbon sequestration.

The most obvious strategy for sequestering carbon dioxide is Carbon Capture and Storage. CCS systems attach to factories and power plants, rerouting the emitted carbon dioxide into storage tanks located in the ground or elsewhere. CCS systems have been found to be extremely effective, capturing anywhere from 80-95% carbon dioxide emissions. Such systems alone have the ability, at full installation levels, to capture approximately 35% of the United States' total carbon dioxide emissions. The EPA has already been ordered by the courts to address emissions at newly constructed power plants and factories. CCS systems are a logical step for plants and factories to fulfill judicial and/or legislative mandates.

Another strategy for limiting CO_2 emissions is natural sequestration. Plants normally use carbon dioxide to complete the vital process of photosynthesis. Therefore, strategic plantings could prove nearly as effective as CCS. Two methods of natural sequestration stood out in our study as the most effective and feasible.

It is first suggested that the United States supports the growth of the algae-based bio-fuel industry. Algae farms, if comprising solely of 1% of the United States arable land, would provide a significant extraction of CO2 from the atmosphere. Such farms would simultaneously provide an effective source of environmentally conscious fuel.

Also, the United States contains an invaluable resource often not thought of when dealing with global climate change: the United States Federal Highway System. The national highways account for over 160,000 miles of government-owned land. If only 50% of these highways included a 25-foot wide strip of switchgrass adjoining to each side, a significant amount of carbon dioxide could be captured, with minimal investment.

In total, these projects tally up to a small sum, in comparison to the total size of the Federal Budget. All three portions of the project cost only $287 Billion to follow through to completion. With the fate of the country's ecological future at stake, it seems a rather paltry sum to put forth.

We firmly believe these simple changes can and will significantly lower the CO_2 emissions of the United States, but this may not be enough. If we are truly concerned about the fate of our nation and planet we need to take further steps to not only control the CO_2 produced but to reduce the total amount our country emits. Sequestration legislation would help but further reduction in the amount of CO_2 produced is critical. Our atmosphere can only handle so much before we permanently modify nature's cycles. Our plan, while effective, can only prolong the inevitable. We, along with the rest of the world, must rise to the occasion and become accountable for our actions. Reversal is possible but not through sequestration alone. We must reduce emissions. Not for ourselves, but for the generations of Americans to follow.

Sincerely,
Team 2157

Appendices

Appendix A: Justification for stated carbon consumption of algae

From the website of a group advocating the proliferation of algae farms:

"We generally assume that the growing areas of the algae farm will be available for growing algae 85% of the year. Similarly, the annual average productivity is estimated at 80 gm/m2-day for our highest productivity system. Thus the overall system productivity is about 25 kilograms per square meter per year (55 pounds).

The overall biomass is expected to be slightly over 50% carbon by weight. Since carbon is 27.3% of the weight of CO_2, it requires approximately 1.9 times the weight of produced biomass in CO_2. Thus for every 1 ton of biomass produced, 1.9 tons of CO_2 are consumed. Multiplying 55 * 1.9 = 104.5 pounds CO_2 consumed per square meter growing area per year. Our standard commercial algae farm includes 100 hectares (247 acres) of algae growing area, which will consume over 52,000 US tons of CO_2 per year. The algae farms are expected to be built in multiple units of the 100 hectare standard for facilities where more CO_2 is available…"[18] ([Online], 2008)

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[17]USDA, (2000, December 12). Working trees for carbon cycle balance. Retrieved November 16, 2008, from NAC Web site: http://www.unl.edu/nac/brochures/wtcarbon/.

Appendix B: Graphs of growth coefficient functions

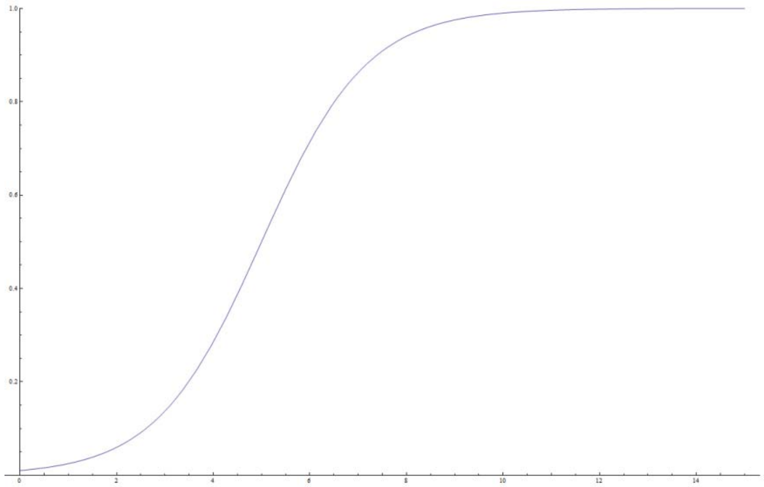

Figure 7. A graph of $C(t)$, the growth coefficient function of algae pools. The function begins to increase slowly, representing the slow start forced by the infrastructure build-up at the beginning of such a venture. The coefficient caps out at one, meaning that the program is fully in place and all algae is absorbing carbon at full efficiency.

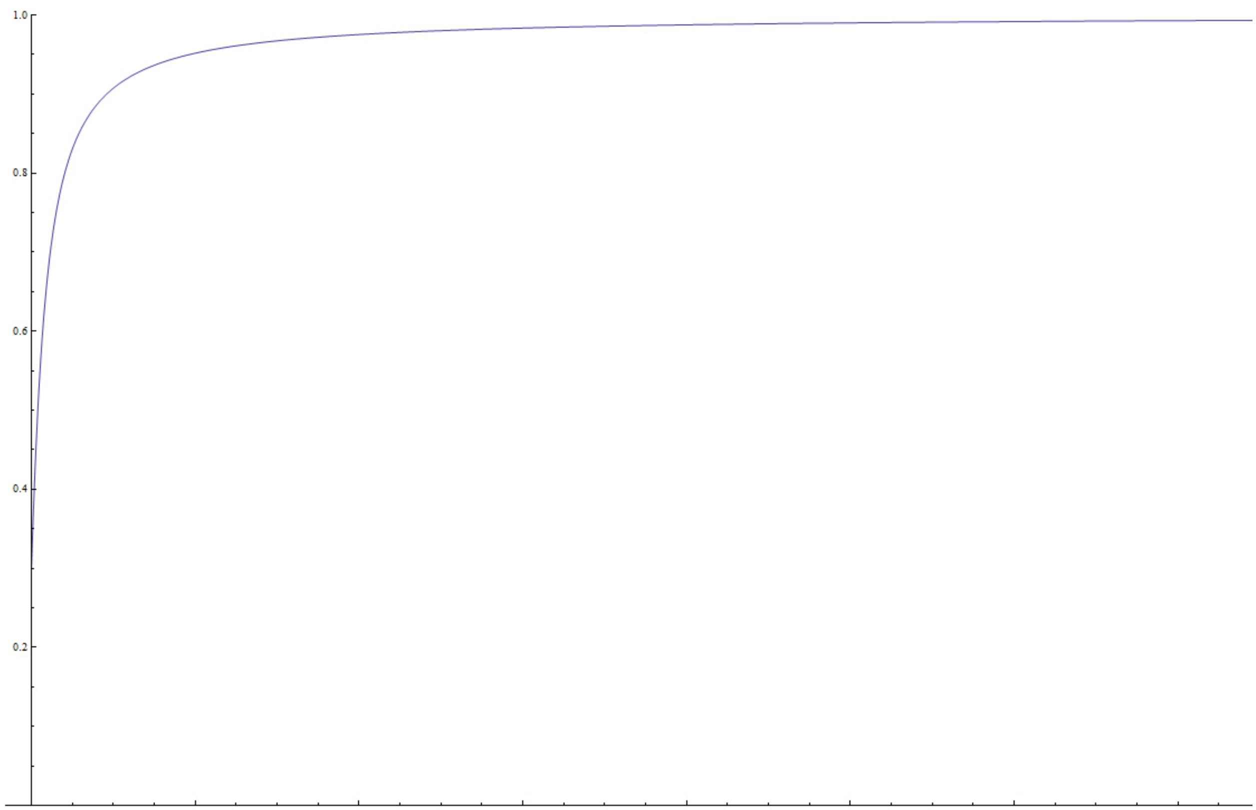

Figure 8. A graph of $G(t)$, the growth coefficient of farmland trees. The function increases fairly quickly to one but is concave down, representing the variable growth of trees throughout their lifetimes.

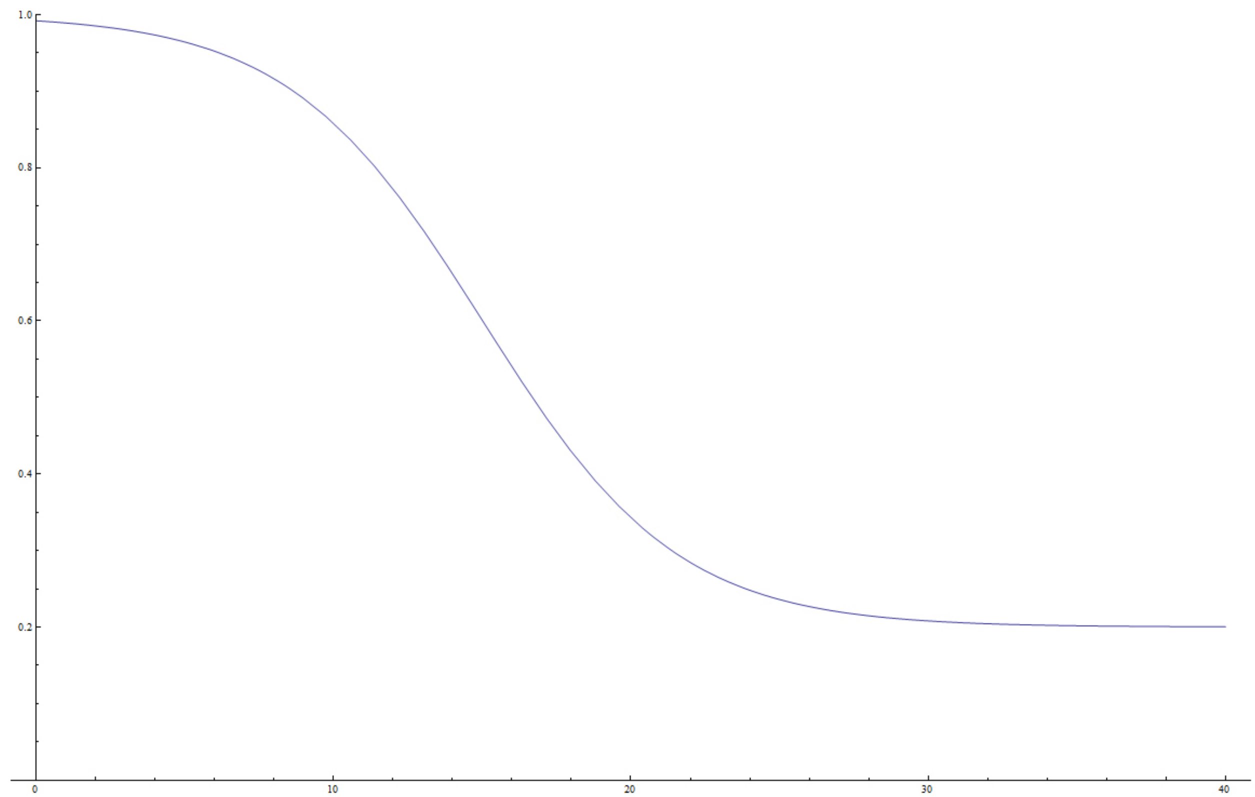

Figure 9. The graph of $V(t)$, an implementation coefficient function for CCS systems. As more factories and power plants implement CCS, their net emissions will decrease. Since the gross emissions are assumed to be constant, the coefficient must be decreasing, as shown by this graph.

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Figure 4- http://algae-biodiesel.com/texas-algae-farm.jpg
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