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**Working Paper**

## Biocarbon: A Model of Energy Use, Forestation, and Climate Change

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Biocarbon: A Model of Energy Use,  
Forestation, and Climate Change

by

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No. 89-9

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## I. Introduction

Although there have been warnings for years of a possible global warming due to the addition of large quantities of carbon dioxide (CO<sub>2</sub>) to the atmosphere, the summer of 1988 brought the issue to the forefront of media attention and policy discussion. During the summer, large parts of the U.S. experienced drought conditions, impacting agricultural output, energy use, and overall comfort levels. While more serious droughts have occurred in the past, such as during the dust-bowl days of the 1930s, there was a definite sense of foreboding associated with this drought.

Statistically, it is difficult to prove the cause of the drought. It could be the onset of a global warming or it could just have been an abnormal year. What is known is that the five hottest years of this century occurred in the 1980s (Figure 1), and that the current global surface temperature is 0.4° Celsius warmer than the mean temperature from 1951 to 1980.<sup>1</sup> James Hansen, director of NASA's Goddard Institute for Space Studies, in testimony before a Senate Committee on June 23, 1988, asserted that he was 99 percent certain that this indicates that a global warming has begun, but admits that it is not possible "to blame a specific heat wave/drought on the greenhouse effect."<sup>2</sup> Indeed other researchers conclude that the 1988 North American drought was the result of natural variations in the coupled atmospheric-oceanic system of the tropical Pacific ocean.<sup>3</sup>

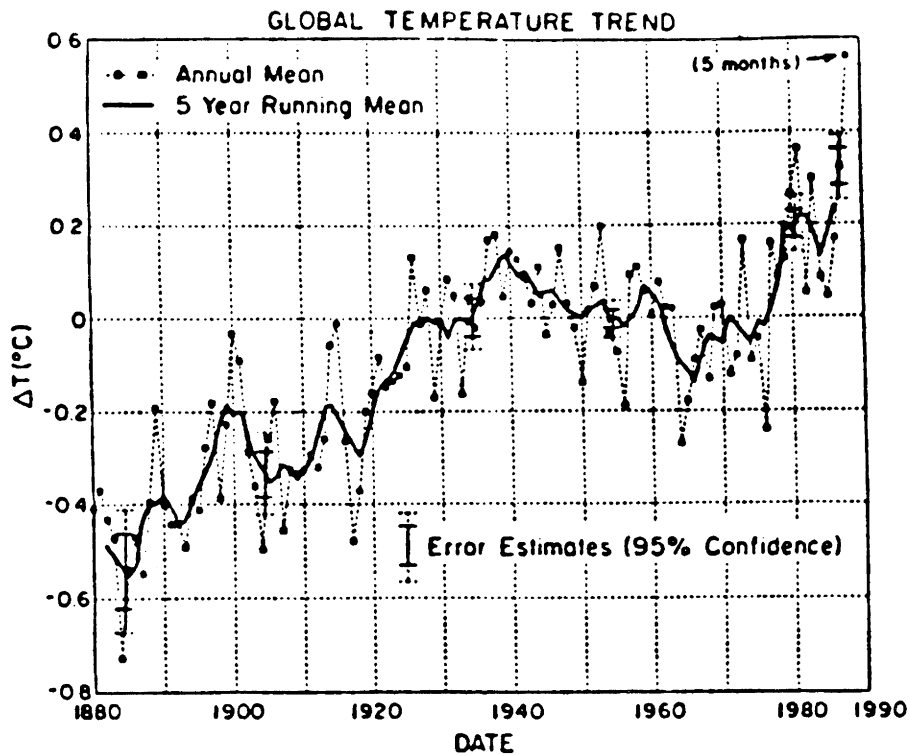


Figure 1

Global surface air temperature change, 1880-1987. The zero point is defined as the mean temperature for the period 1951-1980. The present observed global temperature is close to  $0.4^{\circ}$  Celsius warmer, relative to this thirty-year mean.

Source: J. Hansen, Testimony before Senate Committee on Energy and Natural Resources, June 23, 1989.

Although there are many unknowns with respect to when and how quickly the earth's temperature will rise, scientists have reached a rare consensus: the earth is going to get warmer. Whatever the cause, the drought of 1988 demonstrates how vulnerable we are to variations from the norm in regard to climate, and how delicate the balance is between factors such as good farm yields and crop failure. Figure 2 illustrates the effect of the drought on U.S. corn yields: 1988 yields were 34 percent lower per acre over the

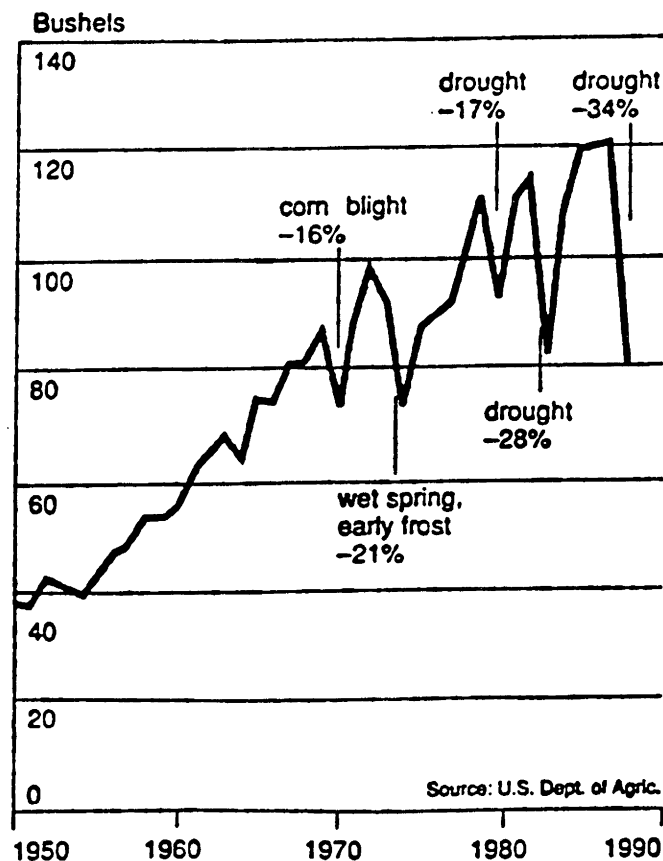


Figure 2

U.S. corn yield per acre, 1950-1988.

Source: Worldwatch, November-December 1988.

previous year.<sup>4</sup> Obviously, if temperatures rise with the intensity and the rapidity that many predict, it will require great changes in our lives, from changing agricultural practices to overall comfort levels.

The purpose of this paper is to summarize what is known about the predicted climate change, including the causes and possible consequences, and then to introduce a simple computer model that allows the user to explore various relationships bet-

ween energy use, forestation, and global temperatures. Rather than presenting results of the model, this paper serves as background information for using the model. The model itself is easy to use but comes with the following warning. Predicting future events is very difficult; few analysts, for example, foresaw the depressed price levels of oil in this decade. The model's value lies in its usefulness in exploring policy initiatives.

## II. Statement of the Problem

Carbon dioxide and water vapor play a crucial role in determining the earth's climate. The atmosphere is largely transparent to incoming visible light which strikes the earth's surface, warming the oceans and the land. Heat is then reradiated back into space with wavelengths in the infrared range. Carbon dioxide and water vapor absorb a percentage of this infrared radiation, resulting in a thermal blanket around the globe. In the absence of these gases, all of the heat radiation would be dissipated back into space, resulting in a cold and lifeless planet (estimated at about 0° Fahrenheit).<sup>5</sup> This effect is often referred to as the greenhouse effect since it is analogous to the trapping of heat inside a greenhouse.

The concern is that as concentrations of these so-called greenhouse gases (such as CO<sub>2</sub>) increase, more and more of the infrared radiation is absorbed and less is dissipated. The result is that global temperatures increase.

Atmospheric concentrations of carbon dioxide began to increase with the onset of the Industrial Revolution around 1860. Although exact measurements of CO<sub>2</sub> were not recorded at the time, analysis indicates preindustrial levels of between 265 and 280 parts per million (ppm). Current readings from Mauna Loa, a national laboratory in Hawaii responsible for monitoring CO<sub>2</sub> levels, indicate that the concentration has increased approximately 25 percent, to 345 ppm.<sup>6</sup> Figure 3 shows the atmospheric concentrations at Mauna Loa. There is an observable, regular, semi-annual oscillation and a clear annual increase.

The largest single source of this CO<sub>2</sub> buildup is from the combustion of fossil fuels. As oil, gas, and coal burn, the carbon released is carbon that was trapped thousands of years ago. Thus, the continued buildup of CO<sub>2</sub> is directly tied to the future use of fossil fuels, whether for electrical generation, transportation, or other industrial and consumer uses. A secondary source is deforestation; forests act as a large carbon sink and clearing of the trees eventually results in the release of their carbon, either through decomposition or burning.

While carbon dioxide has received the most attention to date as a factor in global warming, there are other gases which are also factors. Included in this family of greenhouse gases are nitrous oxides, chlorofluorocarbons, methane, and tropospheric ozone, all shown in Table 1.<sup>7</sup> Recent estimates<sup>8</sup> suggest that these other greenhouse gases may account for 50 percent or more of any greenhouse warming, and hence are also very important



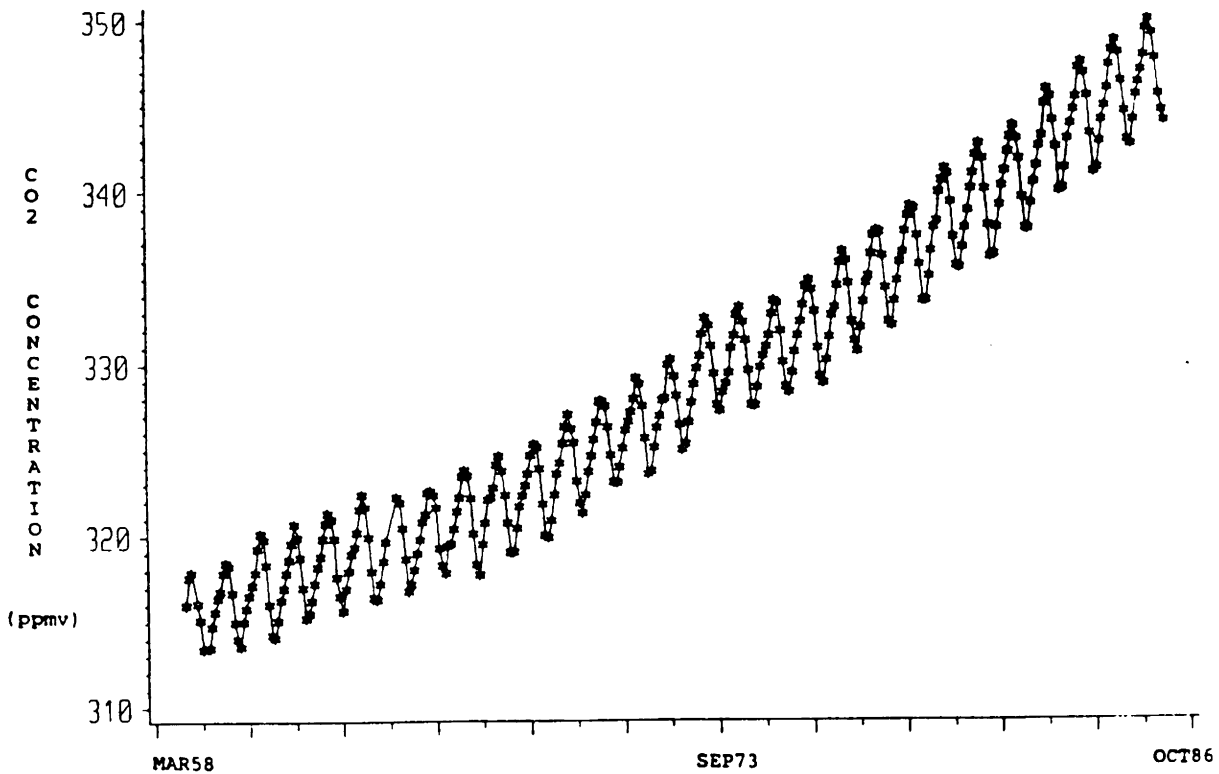


Figure 3

Concentrations of atmospheric CO<sub>2</sub> at Mauna Loa Observatory since 1958.

Source: Keeling 1986.

factors when considering policy alternatives.

Primary sources of nitrous oxides are the combustion of fossil fuels and the decomposition of nitrogen fertilizers. It appears that the release of nitrogen from fossil fuel combustion in the past accounts for virtually the entire increase seen in atmospheric nitrous oxide concentrations to date.<sup>9</sup> However, research suggests that the release of nitrous oxides following field application is very slow. Some studies suggest that it will take hundreds of years for the full nitrogen release to

Table 1  
Important Greenhouse Gases

<u>Name</u>	<u>Formula</u>	<u>Annual Growth Rate</u>
Carbon Dioxide	CO <sub>2</sub>	0.5 %
Nitrous Oxide	N <sub>2</sub> O	0.25 %
Methane	CH <sub>4</sub>	1.0 %
CFC-11	CFCl <sub>3</sub>	7.0 %
CFC-12	CF <sub>2</sub> Cl <sub>2</sub>	7.0 %

occur.<sup>10</sup> So, although agricultural practices may play an important role in future nitrous oxide release, for current modeling purposes, increasing nitrous oxide concentrations reflect emissions from fossil fuel combustion.

Chlorofluorocarbons include a wide range of chemicals and products, often referred to as CFCs. CFC-11 and CFC-12 are the most widely used of the group. Several basic properties, such as a low boiling point, low heat of vaporization, high insulating values, and nontoxicity, have made CFCs ideal for use in a wide range of products, including aerosols, styrofoam products (such as those used by fast-food chains), and refrigerants for refrigerators and air conditioners. Besides their contribution to the greenhouse effect, chlorofluorocarbons also result in the breakdown of atmospheric ozone and have been cited as a primary suspect for the "ozone hole" that was recently detected over Antarctic regions. They are also the first greenhouse gas to be limited by international treaty. The Montreal Protocol, as initially signed

in September 1987 by twenty-four countries, had as a goal 50 percent reduction in CFC use by 1998. In March of 1989 the twelve members of the European Community, all signatories to the treaty, announced a new goal of a total ban by 2000. This came after realization that a 50 percent reduction was not going to prevent serious damage to the ozone layer. Although the treaty evolved out of the realization of CFCs' role in ozone destruction, the treaty serves as a model for negotiations over other greenhouse gases.

Concentrations of atmospheric methane have been increasing at a rate of approximately 1 percent per year over the past thirty-five years.<sup>11</sup> Primary sources of methane are venting during fossil fuel mining and extraction and solid waste management, and biotic sources, such as swamps, termites, cattle, and rice paddies. Estimates vary widely as to the largest source, although recent studies suggest that it is the biotic sources that are probably the largest component.<sup>12</sup> Thus, although policies curbing fossil fuel usage could slow releases from fossil fuel related sources, such policies would have little effect on biotic sources.

The chemical reactions in regard to tropospheric ozone, another of the greenhouse gases, are quite complicated. It appears that while stratospheric ozone levels are decreasing (i.e., the ozone hole), tropospheric levels are increasing as a result of photochemical reactions involving nitrous oxides, methane, and other hydrocarbons.

Sulfur dioxide, the precursor to acid rain, is technically also a greenhouse gas, although since it is frequently washed out of the atmosphere by precipitation, its atmospheric concentrations are negligible.<sup>13</sup> Sulfur dioxide is mentioned here only because any policy aimed at cutting fossil fuel use for the purpose of reducing CO<sub>2</sub> emissions would also reduce SO<sub>2</sub> emissions, a positive benefit worth consideration.

Obviously, these other greenhouse gases are also very important to an overall global warming. However, the largest single greenhouse gas is carbon dioxide, and policies directed at curbing fossil fuel use would also reduce some of these other greenhouse gases, in particular, nitrous oxides, methane (marginally), tropospheric ozone, and sulfur dioxides. Thus, the rest of this paper and the computer model focus exclusively on carbon dioxide emissions and the expected consequences from increasing carbon dioxide. It is important to keep in mind, however, that these other gases do exist and could amplify any CO<sub>2</sub>-induced effect by a factor of two.

### III. Consequences of a Doubling of Atmospheric CO<sub>2</sub>

When referring to possible consequences of a greenhouse warming, it is convenient to use a doubling of CO<sub>2</sub> levels over preindustrial concentrations as a benchmark. Taking 275 ppm to be the preindustrial atmospheric concentration, a doubling occurs at 550 ppm. Recall that the current concentration is approximately 345 ppm.

For a doubling of CO<sub>2</sub>, it is estimated that the mean global temperature will increase approximately 1.5 to 4.5° Celsius, or 2.7 to 8.1° Fahrenheit.<sup>14</sup> Taking the current mean temperature to be 59° F,<sup>15</sup> this implies a future mean temperature of from 61.7 to 67.1° F. The distribution of these increases is not expected to be uniform, with the smallest changes occurring at the equator and the largest changes near the poles. These temperature changes do not occur instantaneously; there is a lag from the time that CO<sub>2</sub> is added to the atmosphere to the date that a temperature change occurs, due largely to the huge thermal mass of the oceans. Thus, this expected temperature change is often referred to as a temperature change commitment, meaning that the future global temperature will be increased as a result of past carbon emissions. Estimates of the magnitude of these lags range from one to several decades.<sup>16</sup>

A likely consequence of a CO<sub>2</sub> doubling will be an increase in the number of extreme weather events, such as droughts, extended hot periods, hurricanes, and tropical storms. For example, Hansen calculated the potential effects for a city such as Washington, D.C. Currently, Washington experiences an average of six days of above-95° F weather per year. Following a doubling, as many as forty-nine days per year would be above 95° F.<sup>17</sup> An obvious negative feedback from this is that as the number of such days increases, the demand for electricity to run air conditioners will increase, resulting in further increases in CO<sub>2</sub> emissions.<sup>18</sup>

Most climate simulations predict that for the prime agricultural areas of the U.S., the climate is likely to be hotter and drier, meaning the displacement of crops such as corn, wheat, and soybeans in a northward direction. This suggests more trouble for U.S. agriculture as farms in the southern states are less suited for conventional crops, and as yields in other major areas suffer from a lack of soil moisture. For other countries, such as the Soviet Union and Canada, a warming might actually improve agricultural conditions.<sup>19</sup> One scenario suggests that following a doubling of CO<sub>2</sub>, the Soviet Union could increase its wheat yields by 49 percent.<sup>20</sup>

As temperatures increase, a sea-level rise will follow. This is due to two factors. First, the uneven global distribution of the change means that the poles will experience the greatest temperature increase. At a minimum, polar ice packs and permafrost would melt around the edges, with the potential for extensive melting of the caps. A second factor is the thermal expansion of the oceans. The combined effect is expected to result in a one- to two-meter sea-level rise for a doubling of CO<sub>2</sub>.<sup>21</sup> Such a rise would mean large inundations of coastal regions. Examples abound of cities, such as Miami Beach, and countries, such as Bangladesh, that would be largely under water given such a rise.<sup>22</sup>

#### IV. The Global Carbon Cycle

Modeling of any aspect of the greenhouse effect requires an understanding of carbon sources and sinks. Figure 4 illustrates

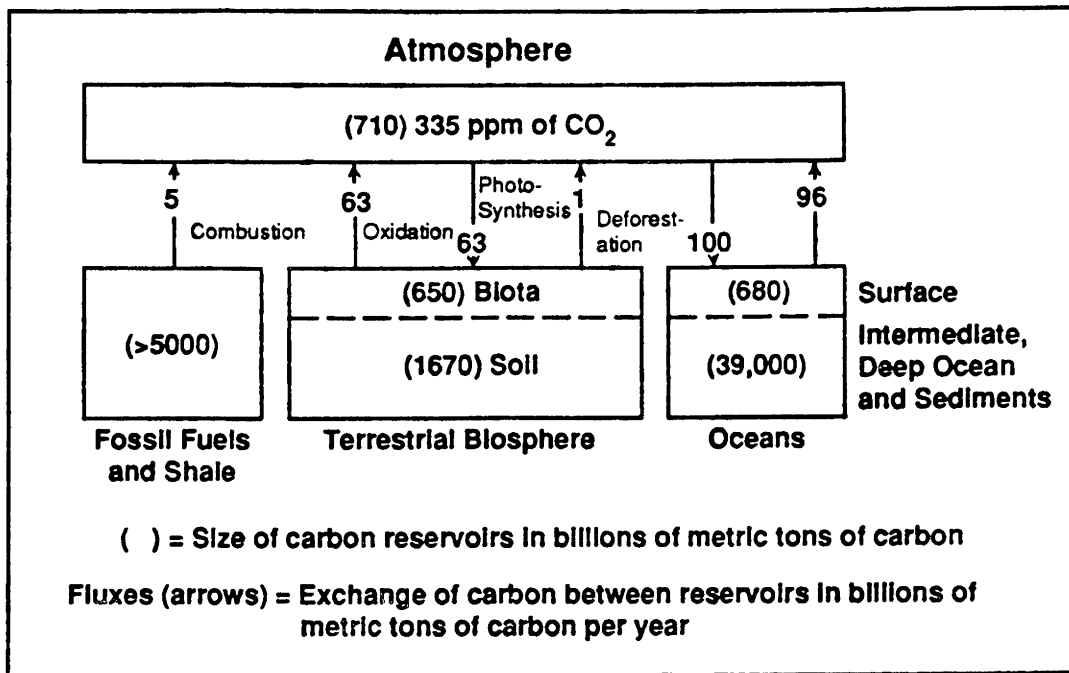


Figure 4

Carbon reservoirs and fluxes.

the four main reservoirs of the global carbon cycle: the atmosphere, fossil fuels, terrestrial biosphere, and the oceans. Arrows between the various reservoirs indicate annual flows or fluxes of carbon. For example, an estimated 5 gigatons (gt) of carbon are released to the atmosphere every year as a result of fossil fuel combustion.<sup>23</sup> Since measurements indicate that the atmospheric reservoir is increasing at a rate of approximately 3 gt per year, it is clear that not all the carbon released from fossil fuels remains in the atmosphere.

The role of the biosphere remains a topic of controversy.<sup>24</sup> It is thought that prior to the Industrial Revolution, a net balance existed between the assimilation of carbon from the atmo-

sphere by photosynthesis and a return via plant respiration.<sup>25</sup> Since that time, human activities have altered that balance; estimates of the current annual releases as a result of land use changes, mainly deforestation, range from 0.6 to 2.6 gt per year.<sup>26</sup> This model assumes a net flux of 1 gt to the atmosphere. Thus, total net annual fluxes to the atmosphere from fossil fuels and the biosphere are approximately 6 gt per year, twice the observed annual rate of atmospheric increase. This implies a 50 percent atmospheric retention rate, hereafter referred to as the airborne fraction. (Assuming a higher contribution from deforestation would imply a lower airborne fraction.)

The carbon that does not remain in the atmosphere is assumed to be taken up by the oceans, the largest of the four reservoirs. The basic interaction for exchange of CO<sub>2</sub> from the atmosphere to the oceans are the differences in partial pressures of the CO<sub>2</sub> in the surface waters and in the atmosphere. Mixing and circulation between the surface waters and the deeper ocean depths eventually move the CO<sub>2</sub> into the deeper waters.<sup>27</sup> While the carbon capacity of the oceans appear to be immense, as concentrations increase, it is predicted that a larger percentage of carbon will remain airborne.<sup>28</sup> There is a vast literature devoted to the complex modeling of the oceans and their uptake, but for the purpose of this model, it is sufficient to state that the oceans act as a net sink for carbon.

The model calculates future concentrations of CO<sub>2</sub> according to a simple airborne fraction model that relates future levels of



atmospheric CO<sub>2</sub> to current levels plus a percentage of future emissions from both fossil fuel and biotic sources:<sup>29</sup>

$$(1) \quad CO_2(t+1) = A * CO_2(t) + [AF * CF * Emit(t)]$$

where CO<sub>2</sub>(t) = atmospheric concentration of CO<sub>2</sub> in year t in parts per million (ppm);

A = 0.99900618 (a decay factor that allows for a preindustrial equilibrium for atmospheric CO<sub>2</sub>);

AF = 0.5 (airborne fraction: percent of carbon released in year t that remains in atmosphere);

CF = 0.4721 (conversion factor: converts billion metric tons of carbon to ppm CO<sub>2</sub>);

Emit(t) = emissions of carbon in year t in billion metric tons.

Table 2 shows global use of fossil fuels in 1985 broken down into three main categories: coal, petroleum, and natural gas.<sup>30</sup> A "quad" of energy is one quadrillion Btus (10<sup>15</sup> Btus). Additional energy consumption includes 12 quads of electrical energy from hydropower, nuclear, and geothermal plants. The emissions of carbon for any year, Emit(t), depends on the quantity of fossil fuels used and the annual contribution from deforestation. One method of projecting future CO<sub>2</sub> levels is to assume an annual growth rate for the three categories of fossil fuel. Emissions for any particular year, t, are then:

$$(2) \quad Emit(t) = BF + [0.027Q_c(1+r_c)] + [0.023Q_p(1+r_p)] + [0.016Q_g(1+r_g)]$$

where BF = 1 (carbon released as a result of deforestation);

Q<sub>c</sub> = quantity of coal consumed in year t-1 (in quads);

Q<sub>p</sub> = quantity of petroleum consumed in year t-1 (in quads);

$Q_g$  = quantity of natural gas consumed in year  $t-1$  (in quads);

$r_c$  = annual growth rate of coal use;

$r_p$  = annual growth rate of petroleum use;

$r_g$  = annual growth rate of natural gas use;

and where the terms 0.027, 0.023, and 0.016 are conversion factors for each of the three respective primary energy types expressed in tons of carbon per quad energy consumed.<sup>31</sup>

Equation (2) basically says that future atmospheric  $CO_2$  levels are tied to the rate of growth in fossil fuel usage. For example, if one assumes a 4 percent annual increase in fossil fuel usage, as was the case in the U.S. from 1940 to 1973, a doubling of the preindustrial  $CO_2$  level occurs in 2036. At a 2 percent rate of growth, the doubling occurs in 2059. If no growth occurs in fossil fuel usage, the doubling is delayed until 2173. Clearly, as with any exponential function, a small change in growth rates makes a very large difference when a  $CO_2$  doubling occurs.

While (2) adequately demonstrates the importance of lowering growth rates in fossil fuel use, it is too simplistic for use in projecting actual future energy demand and resulting  $CO_2$  levels. Other important variables to consider include world population, price paths of the various energy products, and per capita income levels. For example, lowered population growth rates should reduce growth rates of fossil fuel use. Increasing per capita income would tend to increase fossil fuel growth rates, assuming a positive income elasticity of demand; increased fuel prices

Table 2  
1985 Energy Use Statistics

<u>Resource</u>	<u>Quantity Consumed (quads)</u>
Coal	84.5
Petroleum	100.2
Natural gas	<u>57.1</u>
Total	241.8

would lead to decreased growth rates, assuming a negative price elasticity of demand.

Expressing energy demand as a multiplicative function serves as an adequate beginning point:

$$(3) \quad Q = P^b I^c N$$

where Q = quantity of fossil fuel consumed, whether coal, petroleum, or natural gas;

= a constant (see below);

P = price of fuel;

b = price elasticity of demand;

I = per capita income;

c = income elasticity of demand;

N = world population.

This equation can be used on either a global or a regional scale. For a global scale, average values for all market economies combined are used. To use Equation (3) on a regional basis, regions must be selected according to some notion of common properties, such as developing countries, industrial countries, Soviet

bloc countries, and Asian Communist countries. Quantities of fuels used by the various regions would then be aggregated to obtain a global total.

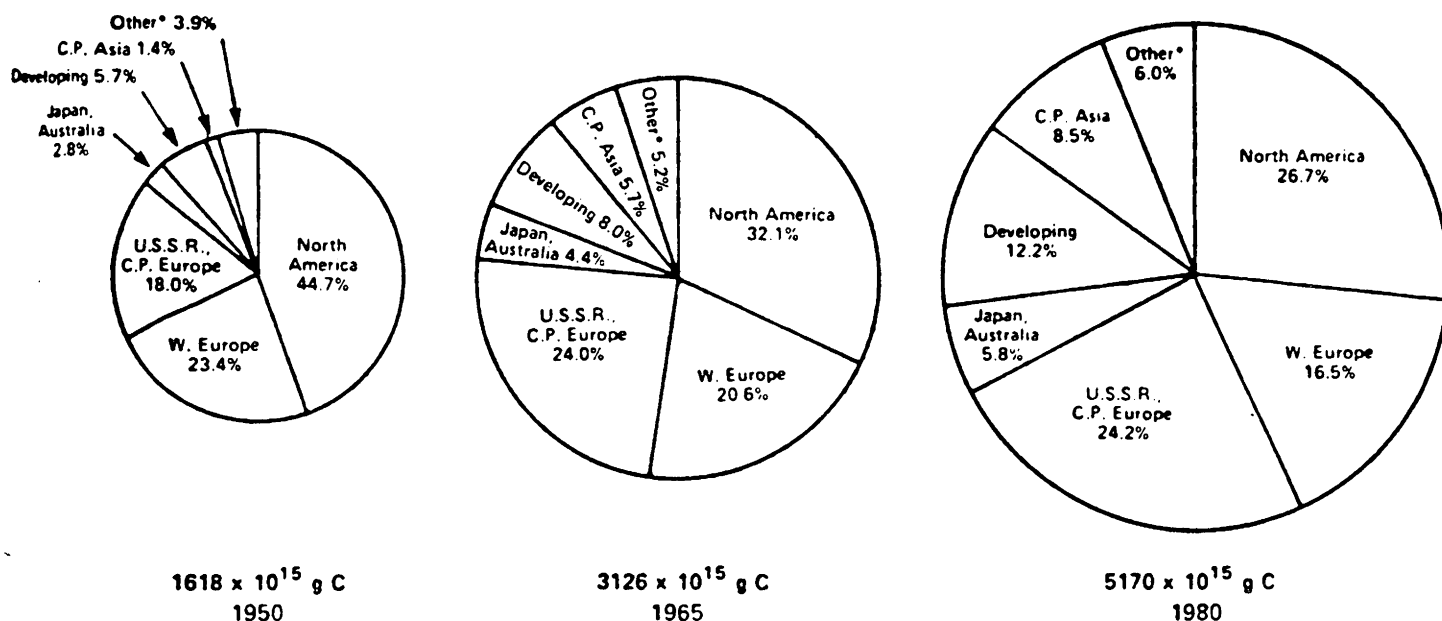
Figure 5 illustrates the importance of regional differentiation by showing the changing patterns of global CO<sub>2</sub> emissions since 1959.<sup>32</sup> Note that while in 1950, North American countries were responsible for 44.7 percent of all CO<sub>2</sub> emissions, in 1980 they were responsible for only 26.7 percent of all emissions. During this same time period, the fraction of total emissions attributable to the People's Republic of China and the developing countries in South America, Asia, and Africa grew from 7.1 percent to 20.7 percent. This demonstrates the importance of considering individual regions of the world in terms of likely growth rates in population, per capita income, and hence fossil fuel consumption.

The model calculates the value of the constant,  $\alpha$ , by substituting current values of energy price, per capita income, population, and user-supplied price and income elasticities of demand. For example, on a global basis, assuming current price and quantity data for fossil fuel use, a price elasticity of demand of -1.0 and an income elasticity of demand of 0.5, both realistic estimates, results in the following three demand equations:

$$Q_c = 0.38P_c^{-1}I^{.5}N$$

$$Q_p = 0.92P_p^{-1}I^{.5}N$$

$$Q_g = 0.86P_g^{-1}I^{.5}N.$$



\*Includes Worldwide Gas Flaring, Fuel in Bunkers, Oxidation of Non-Fuel Petroleum Products.

Figure 5

The changing pattern of global CO<sub>2</sub> emissions.

Source: United States Department of Energy, DOE/ER-0239.

Population,  $N$  in (3), for any year,  $t$ , is given by the function:

$$(4) \quad N = N_0 e^{rt}$$

where  $N_0$  = 1985 population;

$r$  = population growth rate.

Per capita income,  $I$ , in year  $t$  is given by:

$$(5) \quad I = I_0 e^{rt}$$

where  $I_0$  = initial per capita income;

$r$  = per capita income growth rate.

Price is also assumed to follow an exponential growth function:

$$(6) \quad P = P_0 e^{rt}$$

where  $P_0$  = 1985 price of coal, petroleum, or natural gas;

$r$  = price growth rate.

Using (3), (4), (5), and (6), emissions in any year  $t$  are given by a modified version of Equation (2):

$$(7) \quad \text{Emit}(t) = BF + (0.027Q_C/35.6655 * 10^6) \\ + (0.023Q_P/1.59 * 10^8) + (0.016Q_G/1.9505 * 10^9)$$

where the divisors convert, respectively, tons of coal, barrels of oil, and 1000 cubic feet of gas, to quads of energy.

Finally, the temperature change commitment for any given atmospheric concentration of  $CO_2$  is calculated from a logarithmic function constructed to result in a temperature change of  $3^\circ$  Celsius for a doubling of  $CO_2$ :<sup>33</sup>

$$(8) \quad T = (3/\ln 2) + \ln[CO_2(t)/CO_2(\text{init})]$$

where  $T$  = projected mean temperature change (in  $^\circ C$ );

$CO_2(t)$  =  $CO_2$  in year interested in (in ppm);

$CO_2(\text{init})$  =  $CO_2$  concentration prior to 1860 (275 ppm).

According to Equation (8), for a current atmospheric concentration of 345 ppm, the total temperature commitment (as opposed to the actual temperature change) to date is approximately  $1^\circ$  Celsius; as mentioned, the observed temperature change is approximately  $0.4^\circ$  Celsius.

## V. Available Simulations with the Computer Model

Part 1 of the model allows the user to explore the effects of varying the annual growth rates for the three different energy types by calculating when a doubling will occur for any given growth rates. The calculations for this part are based on Equations (1) and (2). For example, entering an annual growth rate of 4 percent in use of all types of fossil fuel results in a doubling of CO<sub>2</sub> in 2036.

Given the results of Part 1 of the model and the severity of the probable consequences of a global warming, the obvious question is: What types of policies could slow or even reverse the onset of a global warming? Unfortunately, as was mentioned previously, it is already too late to escape any effects. So the basic problem is how to slow releases of carbon dioxide into the atmosphere before the results prove catastrophic.

One technical solution is to capture or scrub the CO<sub>2</sub> from the stacks of power plants. Technical estimates suggest that 90 percent removal would require approximately 19 percent of a plant's net capacity.<sup>34</sup> This, and the fact that power plants contribute only about 25 percent of total carbon emissions, make it unclear how economical or effective this option would be. There is also the question of what to do with the carbon dioxide after it has been captured.

A more logical solution is to figure out how to reduce our dependence on carbon-based fuels. From Equation (2), this means making  $r_c$ ,  $r_p$ , and  $r_g$  (the growth rates for coal, petroleum, and

natural gas use) as close to zero as possible, or even negative. Several possibilities exist, such as a switch to solar, biomass, or nuclear power energy systems, or reducing overall energy consumption through increases in energy efficiency.

It appears that major improvements are possible in this latter area. Whereas Part 1 of the model shows that a 1.5 percent annual increase in *energy use* would cause a doubling by approximately 2075, Worldwatch calculates that a 2 percent annual increase in *energy efficiency* could keep CO<sub>2</sub> emissions to under 465 ppm by that same date.<sup>35</sup> Doing this would require a change in mindset of utilities and consumers, but is possible. One simple example is that for every 75-watt light bulb that is replaced with a new, high-efficiency 18-watt fluorescent bulb, 130 kg of carbon would be kept out of the atmosphere. Purchase price of these new bulbs is high, but over their longer lifetime, total costs would be lower for a frequently used light.<sup>36</sup>

Freeman Dyson, in a 1977 article,<sup>37</sup> contemplated other possible solutions. He asked this question: What actions could be taken if, due to the rising level of CO<sub>2</sub>, we run into acute ecological disaster? Possible actions mentioned included the planting of large numbers of fast-growing trees or swamp plants which could fix carbon. His admittedly rough calculations showed that maintaining the atmosphere at a constant level of CO<sub>2</sub>, starting in the year 2000, would require planting 2.7 million square miles of trees, an area 0.77 times the size of the U.S. Planting costs alone for such a massive project were calculated to be at least



\$200 billion. Dyson concluded that although there appears to be no physical or ecological reason that this could not be done, land-use constraints, political pressures, and simple economics would make implementation very difficult.

More recently, other articles with a similar purpose to that of Dyson's have appeared. Most conclude with statements similar to that of Gregg Marland in a study prepared for the United States Department of Energy: "This analysis suggests that although looking to forests to solve the CO<sub>2</sub> problem is unrealistic, reforestation could indeed play a significant role as one component among a variety of measures taken to address increasing CO<sub>2</sub>."<sup>38</sup>

While there are several ways in which biomass could be used to slow a CO<sub>2</sub> doubling, a major problem is that once the trees have matured, if they are burned or allowed to slowly decompose, their carbon is again returned to the atmosphere. Because of this, many of the studies referred to above suggest the need for sequestering the trees upon reaching maturation; schemes such as harvesting the trees and burying them in abandoned mines have actually been mentioned. Perhaps a better idea is to use the mature trees as a fuel source to displace fossil fuel use. In this manner, carbon once removed from the atmosphere would again be returned, but no new carbon would be added. Comparison of a 400-MW coal-fired plant to a 400-MW wood-fired plant indicates that using the wood option could keep as much as 24 million tons of carbon out of the atmosphere.<sup>39</sup>

The second part of the computer model (Option 2) allows the user to explore various biomass options. While Dyson and Marland both calculated the amount of biomass that would have to be planted to offset the entire yearly emissions of CO<sub>2</sub> (currently 5 billion tons per year), this model assumes that this is an unworkable goal and attempts only to partially offset CO<sub>2</sub> emissions by planting trees.

Table 3 lists the assumptions used for these calculations. Trees can be planted either in intensively managed plots, referred to as Short Rotation Intensive Culture (SRIC), or in more traditional forests or natural stands. Table 4 lists the approximate land areas of several countries and forested areas for comparison with estimates generated by this option.

Two simulations are available under the biomass option: 1) to totally offset future increase in CO<sub>2</sub> emissions; or 2) to specify how many acres of trees should be planted. For suboption 1, the user specifies the growth rates for the fuel types and what percentage of the trees are to be planted in SRIC versus natural stands. The model then calculates the year of a CO<sub>2</sub> doubling and how many acres of trees must be planted to offset future increases in CO<sub>2</sub> emissions. Trees are used to create a scenario that is equivalent to one of zero growth rates in Equation (2). Suboption 2 allows the user to specify a policy of planting a certain number of trees every year and then calculates the expected year of a doubling both with and without the tree planting policy.

Table 3  
Assumptions Concerning Biomass Option

	<u>SRIC</u>	<u>Natural Stands</u>
Growth Rates (tons per acre per year)	6.0	1.5
Carbon Content (percent)	50.0	50.0
Time to Maturation (years)	25.0	50.0
Total Carbon Fixed (tons per acre)	75.0	37.5

Table 4  
Land and Forested Area for Selected Countries

	<u>Land Area (million acres)</u>	<u>Percent of Total</u>	<u>Forested Area (million acres)</u>	<u>Percent of Land Forested</u>
World	32,313	100.0	7257	22.4
U. S. S. R.	5502	17.0	1957	35.6
China	2305	7.1	309	13.4
Canada	2278	7.1	652	28.6
U. S. A.	2256	7.0	482	21.4
Brazil	2090	6.5	979	46.8
Australia	1883	5.8	104	5.5

Source: World Resources Institute and the International Institute for Environment and Development 1986. World Resources 1986 (New York: Basic Books).

Part 3 of the model allows the user to explore the impact on future levels of CO<sub>2</sub> of varying price and income elasticities of demand, and growth rates in energy prices, per capita income, and population. The calculations are based on energy-demand Equations (3), (4), (5), (6), and (7). The user is given the choice of applying the model on a global or a regional basis. For the latter, the world is divided into four regions: industrialized countries, Soviet bloc countries, Asian Communist countries, and developing countries not included in the other regions. Table 5 includes the starting assumptions of the model. Appendix A demonstrates the importance of global cooperation in reducing CO<sub>2</sub> emission by showing what happens if China proceeds with rapid industrialization, fueled by its vast coal reserves.

This regional approach allows more insight than Option 1 into the factors affecting future emission levels. For example, the user can experiment with altering future price levels of the various energy types and observe how such pricing policies could effect the expected doubling date. A potential policy might be to tax fuels according to estimated carbon content of fuels in an effort to induce switching to cleaner fuel types: for example, taxing coal heavily while subsidizing natural gas use (or better yet, a noncarbon-based fuel).

## VI. Conclusion

This paper is an introduction for the use of the computer model "Biocarbon: A Model for Analyzing Energy Use, Forestation,

Table 5

## Global and Regional Statistics Used in Part 3 of the Biocarbon Model

1985

	<u>Global</u>	<u>Industrialized Countries</u>	<u>Developing Countries</u>	<u>Soviet Bloc Countries</u>	<u>Asian Communist Countries</u>
Population (billions)	4.885	0.769	2.535	0.431	1.148
Per Capita Income (dollars)	3172.0	13,767.0	712.8	6289.0	328.4
Energy Use (quads)					
Coal	84.5	31.9	9.94	24.87	17.76
Petroleum	100.2	58.9	20.20	17.97	3.10
Natural Gas	57.2	29.3	5.40	22.00	0.48
Energy Costs (dollars)					
Coal (ton)	43.0	43.0	43.0	43.0	43.0
Petroleum (bbl)	30.0	30.0	30.0	30.0	30.0
Natural Gas (1000 ft <sup>3</sup> )	2.32	2.32	2.32	2.32	2.32

and Global Temperature." Option 1 allows the user to explore the relationships between energy growth rates and a CO<sub>2</sub> doubling. Option 2 looks at the use of large scale biomass plantations as a possible policy option to slow the expected warming. Option 3 uses energy-demand equations to explore the relationships between price and income elasticities of demand, growth rates in population, per capita income, price of fossil fuels, and future CO<sub>2</sub> levels.

## Notes

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## Appendix A

### Industrialization of China

A stated Chinese policy is to quadruple its 1980 GNP by the year 2000. To achieve this goal would require a large increase in energy consumption over current levels. China is blessed with two major energy resources that could fuel this industrialization: abundant coal reserves and water suitable for hydropower development. Currently, 80.6 percent of its power needs are met through coal combustion.<sup>1</sup> Obviously, if China, a country with 20 percent of the world's population, strives for higher per capita income levels through industrialization fueled by coal-fired plants, it will make it more difficult to slow global CO<sub>2</sub> emissions.

Option 3 of the model was used to provide a simple example of the effect of industrialization. Option 3 projects a doubling date of atmospheric CO<sub>2</sub> levels based on growth rates in per capita income levels, population, and fuel prices for four regions of the world. Region 4, the Asian Communist countries, is largely dominated by China.

Table A-1 illustrates a base case model where it is assumed that the different growth rates are equal around the world. (For example, per capita income is growing at 1 percent per year, in all four regions). The result is a doubling of atmospheric CO<sub>2</sub> levels in 2090. Under these assumptions, the industrialized and Soviet bloc countries consume 80 percent of all fossil-fuel-generated power before and after the doubling. Thus, presumably under

Table A-1

Scenario 1

Simulation: Energy Demand Equations, 4 region model

ASSUMPTIONS

Percent of carbon that remains airborne: 50 %  
 Constant deforestation contribution: 1 billion tons

Carbon Content of Fuel Types (billion tons carbon/quad energy)

Natural gas .016  
 Petroleum .023  
 Coal .027

Legend: 1 = Industrialized Countries      2 = Developing Countries  
 3 = Soviet Bloc Countries              4 = Asian Communist

	1	2	3	4
Energy use in 1985 (Quads)				
Natural gas	29.3	5.4	22.0	.5
Petroleum	58.9	20.2	18.0	3.1
Coal	31.9	9.9	24.9	17.8
Share of world energy use	.5	.1	.3	.1
Annual Price Change				
Natural gas	1 %	1 %	1 %	1 %
Petroleum	1 %	1 %	1 %	1 %
Coal	1 %	1 %	1 %	1 %
Price elasticity of demand	-1	-1	-1	-1
Population in 1985 (billions)	.769	2.54	.43	1.15
Population growth rate (percent)	1	1	1	1
Per capita income in 1985	\$ 13767.5	712.8	6289	328.4
Per capita income growth rate	1	1	1	1
Income elasticity of demand	.5	.5	.5	.5

RESULTS

Doubling occurs in 2090

	1	2	3	4
Energy use in 2090 (Quads)				
Natural gas	49.3	9.1	37.0	.8
Petroleum	99.1	34.0	30.2	5.2
Coal	53.7	16.7	41.8	29.9
Share of world energy use	.5	.1	.3	.1
Population in 2090: (billion)	2.200	7.246	1.234	3.281
Per capita income in 2090:	\$39343	\$ 2037	\$17972	\$ 938

Temperature change committed to by the doubling is 3.0 degrees Celsius  
 or 5.4 degrees Fahrenheit

such a scenario, a treaty on reduction in global CO<sub>2</sub> emissions signed by these two regions would have a large impact.

Table A-2 illustrates what happens to this balance should China succeed in implementing a rapid industrialization policy fueled largely by coal-fired plants. For Regions 1-3, the assumptions from Table A-1 remain unchanged but China achieves an annual growth rate in per capita income of 5.2 percent with a 1.2 percent growth rate in population (the current situation for population). Two results are noteworthy: 1) the projected doubling date is moved up fifteen years to 2075; and 2) by the doubling date Region 4 (China) is the largest consumer of fossil-fuel-generated power.

The point of this example is clear. China is currently an impoverished country with vast coal resources with which they could conceivably industrialize much like the rest of the world did following World War II. And while the Chinese currently are relatively minor contributors to global CO<sub>2</sub> emissions, fulfillment of their industrialization goals would make them a very large source, a point worth considering when seeking to implement CO<sub>2</sub> reduction initiatives.

#### Notes

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Table A-2

## Scenario 2

Simulation: Energy Demand Equations, 4 region model

## ASSUMPTIONS

Percent of carbon that remains airborne: 50 %  
 Constant deforestation contribution: 1 billion tons

Carbon Content of Fuel Types (billion tons carbon/quad energy)

Natural gas	.016
Petroleum	.023
Coal	.027

Legend: 1 = Industrialized Countries      2 = Developing Countries  
 3 = Soviet Bloc Countries              4 = Asian Communist

	1	2	3	4
Energy use in 1985 (Quads)				
Natural gas	29.3	5.4	22.0	.5
Petroleum	58.9	20.2	18.0	3.1
Coal	31.9	9.9	24.9	17.8
Share of world energy use	.5	.1	.3	.1
Annual Price Change				
Natural gas	1 %	1 %	1 %	1 %
Petroleum	1 %	1 %	1 %	1 %
Coal	1 %	1 %	1 %	1 %
Price elasticity of demand	-1	-1	-1	-1
Population in 1985 (billions)	.769	2.54	.43	1.15
Population growth rate (percent)	1	1	1	1.2
Per capita income in 1985	\$ 13767.5	712.8	6289	328.4
Per capita income growth rate	1	1	1	5.2
Income elasticity of demand	.5	.5	.5	.5

## RESULTS

Doubling occurs in 2075

	1	2	3	4
Energy use in 2075 (Quads)				
Natural gas	45.7	8.4	34.3	5.8
Petroleum	91.9	31.5	28.0	37.5
Coal	49.8	15.5	38.8	214.6
Share of world energy use	.3	.1	.2	.4
Population in 2075: (billion)	1.893	6.237	1.062	3.381
Per capita income in 2075:	\$33863	\$ 1753	\$15468	\$35392

Temperature change committed to by the doubling is 3.0 degrees Celsius  
 or 5.4 degrees Fahrenheit

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