Investigation of the effects of stratospheric sulfur injection on terrestrial autotroph productivity via experimentation with diffuse radiation controlled greenhouses

Massachusetts Institute of Technology
Department of Civil and Environmental Engineering

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Executive Summary

Population growth and the development of more energy demanding technologies have led to an increase in fossil fuel combustion since the Industrial Revolution. As a byproduct of fossil fuel combustion greenhouse gases have reached unprecedented levels in the atmosphere. The disruption of Earth's equilibrium has resulted in the development of several schemes to mitigate global climate change, one of which is geoengineering - the intentional manipulation of the environment on a planetary scale.

The focus of this proposal will be on the unintended consequences of one particular geoengineering scheme: the injection of sulfur aerosols into the stratosphere. Increasing the concentration of sulfate particles in the atmosphere will increase Earth's albedo, as these particles reflect some of the sun's radiation back into space. Large-scale injection of sulfate aerosols into the stratosphere can result in unintended consequences such as acid rain, ozone depletion, and effects on terrestrial productivity.

The experiment described in this proposal was designed to enlighten our understanding of the implications of stratospheric sulfur injection and yield a better idea of the practicality of large-scale application. The experiment utilizes a series of diffuse radiation controlled greenhouses that intend to mimic the affect that sulfate aerosols have on incoming radiation by use of different greenhouse glazing materials. The goal is to understand how a change in radiation brought about by stratospheric sulfur injection affects terrestrial autotroph productivity. The results of this experiment will help to create a more comprehensive and full understanding of the unintended consequences of injecting sulfur into the stratosphere.

The proposed experiment investigates the effect that alteration of radiation brought about by stratospheric sulfur injection has on terrestrial productivity. Our results will show either a positive correlation between alternation of radiation and productivity or they may reveal a negative relationship. If the results do reveal that increased concentrations of sulfate aerosols result in increased autotrophic productivity we are actually finding that this particular geoengineering scheme is dually effective in that it cools the planet by deflecting radiation *and* increases the carbon sink potential of terrestrial autotrophs. The ability of stratospheric sulfur injection to mitigate global change in more than one way would increase the viability of injecting sulfur into the stratosphere as opposed to other geoengineering schemes.

An Introduction to Global Climate Change

Since Earth's formation there have been dramatic and cyclic variations in global climate. The planetary climatic condition is the result of a complex system dependent on many factors including Earth's orbital behavior and the orientation of its axis, continental arrangement, greenhouse gas concentrations, predominant life forms, and the strength of the sun's incident radiation (Desonie). Cyclic changes between glacial periods and interglacial periods are observed on a geological time frame. A significant concern of modern times is that the growing human population has induced global climate change through the liberation of copious amounts of anthropogenic greenhouse gases. As a result of these emissions, we have transformed atmospheric conditions and the biosphere at large in little more than a century.

The Industrial Revolution of the eighteenth and nineteenth centuries resulted in innumerable technological and scientific advancements. Unfortunately, many detrimental environmental effects accompanied these improvements. Fossil fuel combustion was used as a source of energy long before the Industrial Revolution. However, the reliance on fossil fuel grew exponentially during this time due to significant population growth and the development of more energy demanding technologies. Carbon dioxide, a radiative forcing greenhouse gas, is a byproduct of fossil fuel combustion. Thus anthropogenic carbon dioxide emissions have grown since the pre-Industrial era from almost nothing to an annual average of approximately six billion metric tons (Garrett, 1992). Today, carbon dioxide concentrations are over 100 parts per million higher than the 280 ppm concentration in existence prior to the Industrial era (Bala, 2009). It is clearly evident that the momentous anthropogenic rise in carbon dioxide began during the time of the Industrial Revolution (Figure 1).

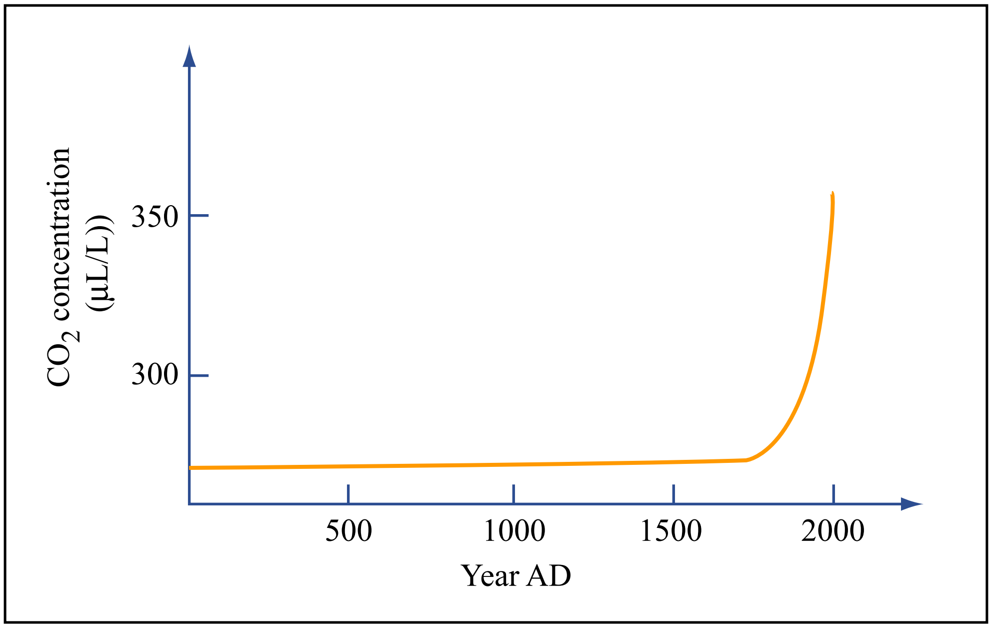

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Figure 1 Atmospheric Carbon Dioxide concentration over the past 2000 years. (Vitousek, 1994).

The troubling aspect of carbon dioxide growth is that the anthropogenic increase of the past few centuries is comparable to concentration changes observed in glacial/interglacial transition periods (Vitousek, 1994). Natural climatic transitions occur over a long period of time such that adaptation can occur. In contrast, human induced changes have occurred at ten times this natural rate (Vitousek, 1994). The escalated pace of climate change will require more rapid adaptation. For that reason, fossil fuel combustion and its rapid effects threaten the future of many existing species.

In the past, the biogeochemical carbon cycle operated through a balanced cycle of exchange. Carbon dioxide primarily entered the atmosphere via respiration and the decay of organic matter. Photosynthesis and deep ocean storage then provided the mechanisms to balance this system by removing atmospheric carbon dioxide. The anthropogenic increase in carbon dioxide through fossil fuel combustion, deforestation and concrete manufacturing, although small in comparison with natural contributions, has disrupted this balance (Garrett, 1992). As displayed in figure 2, the carbon cycle does not have the means to handle the elevated atmospheric carbon dioxide concentration and it follows that much carbon dioxide remains in the atmosphere.

Figure 2 Annual fluxes of the sources and sinks of the global carbon cycle in billions of metric tons of carbon. Sources and sinks flow into reservoirs such as terrestrial soil and vegetation and deep-sea sequestration. Sources and sinks include photosynthesis, decomposition and fossil-fuel combustion and are represented by arrows in the figure (Garrett, 1992).

Global warming is observed because an increase in greenhouse gas concentration results in the decrease of unabsorbed radiation escaping back into space. About 30% of the sun’s radiation reaching Earth is emitted back into space prior to any atmospheric absorption (Garrett, 1992). Then the impinging radiation interacts with greenhouse gases, such as methane, carbon dioxide, nitrous oxide, water vapor and ozone, and is reradiated in the form of infrared radiation (Garrett, 1992). The result is a warming effect on Earth’s surface greater than that which can be explained by the sun’s incident radiation alone (Grassl, 2009). This is known as the greenhouse effect.

Rapid global climate change has large-scale ecological effects on the biosphere. The increase in carbon dioxide, a reactant in photosynthesis, allows for the increase of photosynthetic rates. Some autotrophic species are able to adapt to the environmental change more quickly than others and will therefore gain a competitive advantage from increased carbon dioxide (Fajer, 1989). Another ecological problem arises in that the plants that do take advantage of carbon dioxide more effectively will be producing tissues with lower nutrient concentrations (Fajer, 1989). Therefore the growth rates of herbivores, decomposers, and other organisms further along the food chain will be hindered and the survival of such populations will be threatened (Fajer, 1989). Global climate change also affects biodiversity because as the locations of specific ecological environments shift species will need to redistribute themselves in order to survive. For example, the four degree Celsius rise of freshwater temperature expected in the near future will restrict the range that certain freshwater species can survive to a smaller latitudinal range. (Heino, 2009).

The global climate change stimulated by human action will have a large influence on our species as well. Glaciers in the arctic regions have already begun to melt and in consequence seawater elevation is rising. It is predicted that within this century seawater elevation will rise between .18 and .59 meters (Dupont, 2008). This could render fertile coastal land unproductive and provoke food shortages. In addition to temperature rise, global climate change will encompass fluctuations in rainfall patterns. Rainfall fluctuations could create new areas of water shortages, thereby increasing the number of people with inadequate water supply (Dupont, 2008).

The conditions that exist on Earth are the result of ecological evolutionary adaptations that have taken place over the course of millennia (Remmert, 1980). The human species can exist only in the conditions that are now present (Remmert, 1980). Our own anthropogenic emissions threaten our species and the world at large. Global climate change and its effects have recently gained much publicity and have instigated growing concern of what the future may hold. Scientists and policymakers have been trying to discover practical, efficient methods to ameliorate the impact of human induced climate change. Geoengineering has arisen as a potential strategy that involves the intentional manipulation of the environment on a planetary scale.

Geoengineering

Large-scale manipulation of the environment is not a geoengineering innovation; the idea has been around for quite some time. In fact, Arrhenius predicted the effects of significant fossil fuel combustion as early as 1905 (Keith, 2000). Although the analysis of Arrhenius and his contemporaries focused on agricultural benefits that would arise from increased carbon dioxide, their predictions did hint at the idea of environmental manipulation. In the 1960's a scheme very similar to today's geoengineering arose known as weather and climate modification (Keith, 2000). The United States and the U.S.S.R. planned to manipulate the environment via macro-scale engineering schemes. Both geoengineering and weather and climate modification have scale and intent in common; however, the intent of the two are quite different. The goal of weather and climate modification was to improve the natural climate and palliate natural hazards, while geoengineering aims to mitigate anthropogenic climatic effects. Since the 1960s the seriousness of carbon dioxide concentration growth has been realized and emphasis has shifted from improving the natural climate to saving the natural climate.

Figure 3 Major geoengineering schemes including nutrient addition, reforestation, increasing surface albedo and the injection of stratospheric aerosols. The black arrowheads are indicative of short wave radiation reflected back into space while the white arrows symbolize carbon movement (Lenton, 2009).

Geoengineering strategies can be divided into two principle categories; schemes that reduce the amount of solar radiation absorbed by Earth and schemes that increase the amount of radiation emitted (Figure 3).

The reduction of radiation absorption can be accomplished by limiting the quantity of solar radiation that impinges upon the atmosphere in the first place or by increasing Earth's reflectivity or albedo. Proposed methods to reduce incoming radiation are the placement of reflective sunshades at the Lagrange point between the Sun and the Earth where gravity is minimized or placing smaller mirrors into orbits around Earth (Bala, 2009). Albedo enhancement can be accomplished through the injection of sulfur into the stratosphere, increasing cloud condensation nuclei, or even increasing urban albedo by painting roofs white (Lenton, 2009).

The other branch of geoengineering schemes expands off of the idea that the greenhouse effect can be mitigated by the removal of excess carbon dioxide. These schemes typically involve the transfer of atmospheric carbon dioxide to terrestrial systems, to the deep ocean, or to deep geological formations (Bala, 2009). Of the presented geoengineering schemes, this discussion will focus on the injection of sulfur into the stratosphere.

Geoengineering by the Stratospheric Injection of Sulfur

It is likely that volcanic eruption was the inspiration for the geoengineering method of stratospheric sulfur injection. Volcanic eruptions release large quantities of various gases, including sulfate aerosols, into the atmosphere (Brovkin, 2009). In the first few years after a volcanic eruption, a cooler climate may be observed due to sulfate aerosols responsible for increased albedo. In a volcanically inactive year sulfate stratospheric additions total about 0.1 teragrams (Rasch, 2008). The eruption of Mount Pinatubo resulted in a stratospheric sulfur addition of 100 times the annual contributions of inactive years (Rasch, 2008). This geoengineering method is based upon the ability of stratospheric sulfate aerosols to increase reflectivity, as it is known to do in the case of volcanic eruptions. The natural and artificial methods of sulfur injection are shown in figure 4.

Figure 4 Stratospheric sulfur injection mimics volcanic eruption. Both processes increase sulfate aerosol concentration and increase planetary reflectivity. Source: http://www.nature.com/ nature/journal/v447 /n7141/full/447132a.html

The geoengineering scheme departs from the volcanic eruption analogue in that the sulfur must remain in the stratosphere in order to mitigate the radiative imbalance. There are many reasons why sulfur injection must take place in the stratosphere rather than the troposphere. First of all, anthropogenic sulfur emissions in the troposphere have resulted in acid rain (Kravitz, 2009). Secondly, the mean residence time of sulfur in the troposphere is only about a week while that of sulfur in the stratosphere is on the order of a few years (Crutzen, 2006). The longer mean residence time of sulfur in the stratosphere means that it will be possible for the sulfate aerosols to achieve a higher degree of dispersal and will require less frequent injections. Although this method of geoengineering involves a large change in stratospheric sulfur content, when taken into the context of the atmosphere at large the net sulfur change is not as significant and therefore less likely to produce undesirable environmental effects.

Several methods have been proposed for the physical addition of sulfur to the stratosphere. All injections will be strategically located near an upward bound flow within the stratospheric circulation system to encourage thorough distribution and longer stratospheric lifetime (Crutzen, 2006). Proposed methods of injection include use of artillery shells and balloons to carry sulfur up to the stratosphere and release it once there. Other methods include sulfur injection via aircraft jet exhaust and long-term plume processing (Rasch, 2008). It is estimated that the annual addition of approximately 5 teragrams of sulfur could balance the warming effect caused by doubled carbon dioxide concentration (Crutzen, 2006).

Many factors influence the effectiveness of sulfate aerosols upon their injection into the stratosphere. Many of the proposed methods involve the transformation of injections from hydrogen sulfide and diatomic sulfur to sulfur dioxide and eventually to sub-micrometer sulfate particles (Crutzen, 2006). Particle growth is a function of vapor deposition and concentration of the sulfur compound in question (Rasch, 2008). Lower concentrations of sulfur correspond with lower partial pressures and the particles remain small (Bauman, 2003). Higher concentrations of sulfur compounds, such as those experienced after volcanic eruption, result in an increase in particle size. There is an inverse relationship between particle size and the ability to scatter light efficiently: smaller particles are more effective albedo enhancers than larger sulfur particles (Bauman).

Since geoengineering involves the manipulation of the environment on a planetary scale, the associated effects will be felt worldwide. Although geoengineering intends to mitigate global warming, there is a possibility that negative consequences may arise. It is very difficult to understand the full range of effects that geoengineering schemes could entail because there are innumerable variables in ecological science. Thorough experimentation must be conducted and the long-term effects of geoengineering must be more completely understood before we should consider geoengineering as the best solution to the global climate change dilemma at hand.

Potential Effects of Stratospheric Sulfur Injection

Several potential unintended consequences of stratospheric sulfate aerosol manipulation have already been focal points of debate. The destruction of ozone, sulfur depositions, and effects on the terrestrial biosphere, which will be the primary focus of this proposal, are prospective unintended consequences.

Ozone Destruction

The analog between volcanic eruptions and geoengineering by the injection of sulfate aerosols into the stratosphere may hold true for the effect on ozone as well. The 1982 El Chichon eruption released 3 – 5 terragrams of sulfur into the atmosphere and brought about destruction of approximately 16% of the ozone at an altitude of 20 km in mid-latitude regions (Hofmann, 1989).

The physical ability of sulfate aerosols to destroy ozone relies on several factors. Sulfur particles provide a surface that chlorine can utilize to become more reactive and capable of ozone destruction. An increase in sulfur aerosol concentration therefore involves an increase in the potential for the activation of chlorine (Tilmes, 2008). There is a direct relationship between the potential for the activation of chlorine and ozone loss (Figure 1). By association we can then say that the manipulation of sulfate aerosols will result in increased ozone loss.

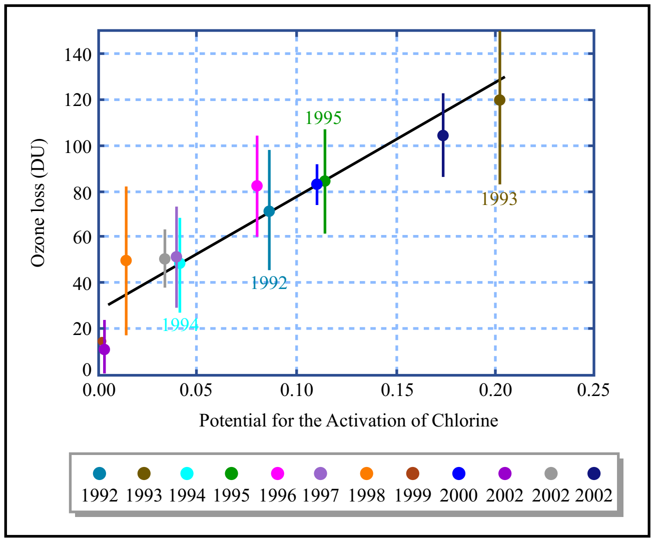

Figure by MIT OpenCourseWare.

Figure 1 The linear relationship between the potential for chlorine activation and ozone loss (Tilmes, 2008)

The potential for ozone depletion is greatest in high latitudes because the chlorine is most reactive in the presence of cold sulfur surfaces (Tilmes, 2008). The Arctic regions have already experienced ozone destruction due to chlorofluorocarbons and are therefore very vulnerable to further depletion or prolonged ultraviolet exposure. Ozone depletion and delayed ozone renewal are important repercussions of stratospheric sulfur injection because they involve increased ultraviolet radiation that causes skin cancer, endangers plants and reduces phytoplankton populations (Aucamp, 2007).

Sulfur Deposition

One reason for injecting sulfur into the stratosphere as opposed to the troposphere is the longer mean residence time of sulfur. In the stratosphere the mean residence time of sulfur is one to two years while that in the troposphere is only about one week (Crutzen, 2008). Although this strategy of atmospheric sulfur injection does prolong a sulfur particle's lifetime in the atmosphere, at some point the sulfur will fall into the troposphere and eventually deposition at the surface will occur. A major concern is that the sulfate aerosols will hydrate resulting in acidic sulfur deposition and harmful environmental consequences (Kravitz, 2009).

It has been estimated that acidic depositions due to stratospheric sulfur injection will be negligible compared to that due to pollution (Robock, 2008). Experiments have been done to investigate acid deposition associated with sulfuric stratosphere injection and have produced results that support the previous estimate. That is, the values of acid deposition are below critical levels that would negatively affect most ecosystems (Kravitz, 2009). Environments without adequate methods of buffering acidity, such as freshwater ecosystems, are vulnerable to harm by increased acid deposition (Kravitz, 2009).

Effect on Terrestrial Productivity

There is still much uncertainty associated with the potential effects of sulfuric stratosphere manipulation on the terrestrial biosphere. The intent of injecting sulfur dioxide into the stratosphere is to increase the planet’s albedo and thereby reflect more incident radiation back into space. Aerosols also have another effect on incoming radiation; as light enters the aerosol-enriched stratosphere it will be reflected and reradiated such that diffuse radiation reaching the surface will increase.

The photosynthetic process is dependent on light. Thus, variations in light brought about by albedo enhancement will affect rates of photosynthesis and consequently plant growth and primary production. By removing carbon dioxide from the atmosphere photosynthetic organisms play an integral part in the biogeochemical carbon cycle. In the global climate change dilemma that we face today the efficiency of terrestrial carbon sinks is of critical importance.

Estimates concerning the effect of increased sulfate aerosols on terrestrial productivity have been made and experiments to test these theories have been conducted. Some experts have reasoned that the reduction in incoming solar radiation will decrease the photosynthetically active radiation impinging upon the terrestrial biosphere and negatively affect net primary productivity (Govindasamy, 2002). But a thorough review of relevant literature reveals that there is not a consensus on this issue.

Other predictions have been made stating that a geoengineered stratosphere will actually increase the diffuse radiation reaching the Earth's surface (Gu, 2003). At first it may seem counterintuitive that this albedo enhancement method would result in increased diffuse radiation because it involves deflecting incoming direct radiation. Injection of sulfur into the stratosphere does decrease the total global solar radiation, a sum of the diffuse radiation and direct radiation (Gu, 2003). However, increased stratospheric aerosol concentrations results in an increase in diffuse radiation (Gu, 2003).

Experimentation has already tested the effect of modified radiation intensities on terrestrial productivity but there is room for improvement. The lack of a consensus among experts reflects that the many complex factors impacting the relationship between a sulfate aerosol enhanced stratosphere and terrestrial productivity make accurate prediction extremely difficult (Gu, 2003; Wuebbles, 2001; Govindasamy, 2002). Further experimentation to prove and expand upon past results is necessary to better understand what global aerosol manipulation will mean for net primary productivity.

A Review of Relevant Past Experiments

A 2001 study by Wuebbles et al. found that a 1.8% decrease in solar radiation did not cause any significant reduction in net primary productivity (Wuebbles, 2001). A similar experiment by Govindasamy reproduced similar results and it was concluded that small variations in incident sunlight would not have a significant effect on plant productivity (Govindasamy, 2002). These studies made use of climate modeling technologies and Govindasamy acknowledges that his experiment lacks a representation of the oceanic system and potential feedbacks that it may involve (Govindasamy, 2002). Climate models are still being developed and perfected so that they can address the complex components of the biosphere as accurately as possible. But this is an ongoing field of research and thus no climate model is without imperfection. An in situ experiment that produced results similar to that produced by climate modeling would strengthen the reliability of the climate modeling result: that stratosphere aerosol manipulation does not significantly affect primary production.

Experimentation via Diffuse Radiation Controlled Greenhouses (DRCG)

Uncertainty still exists in regard to the effect of stratospheric sulfur injection on terrestrial productivity. Because the earth system is very complex and therefore difficult to model past experimentation has yielded inconsistent conclusions. The proposed experiment makes use of diffuse radiation controlled greenhouses (to be abbreviated DRCG) for a long-term investigation of the effect of a geoengineered stratosphere on productivity.

Hypotheses of the DRCG experiment

I. Because the injection of sulfate aerosols into Earth's stratosphere will result in increased levels of diffuse radiation there will be an increase in terrestrial autotroph productivity.

II. The injection of sulfate aerosols also results in decreased direct radiation, which will act to lower primary productivity. However, the net change in productivity will be positive because plants are able to make better use of diffuse radiation than they can of direct radiation.

III. Increased stratospheric aerosol concentration may not have a significant effect on terrestrial autotrophs at first. However, the ability of some plants to make better use of diffuse radiation than others could modify biodiversity in the long run.

Recreating the Terrestrial Biosphere for Experimentation

The only way to completely understand the full range of effects brought on by stratosphere aerosol manipulation would be to implement this geoengineering scheme on a global scale. However, this is a catch-22; we cannot put the biosphere at risk without knowing the range and severity of the consequences. Instead, we design experiments to mimic the biosphere to the best of our ability.

To test the effect of manipulated radiation on productivity this experiment will make use of a series of greenhouses. Each greenhouse will contain an isolated ecosystem modeled after three ecosystems that greatly contribute to global primary productivity. The ecosystems to be replicated in the greenhouses include tropical rain forests, temperate deciduous forests and grasslands. Two greenhouses will be placed at each location: one control and one DRCG. The greenhouses will contain a ventilation system to control the temperature when it has become too hot or too cold. There will also be a plumbing system to maintain the correct level of moisture in the soil and air.

The greenhouse environments will mimic the environments they represent. They will be placed in their natural environment so as to receive the natural amount of incident sunlight. This means that the tropical rainforest greenhouse will be placed in Brazil, the temperate deciduous forest greenhouse in New York and the grassland greenhouse in Texas.

The environment of the tropical rainforest greenhouse will be specifically modeled after Latin American rain forests and will therefore be kept at a temperature of 26° C and receive 4000 mm of precipitation each year (Smith, 2001). Plant species will include mango trees, yagrumo macho and trumpet trees but the replicated biodiversity will not be limited to these few listed species because rainforests are especially diverse ecosystems (Lopes, 2009).

The temperate deciduous forest greenhouse will be characterized by European beech, ashes, birches, and elm trees (Smith, 2001). The temperature should vary seasonably with the surroundings between average lows of 20° F and highs of about 70° F, with about 980 mm of precipitation a year (National Weather Service, 2009).

The Texas grassland greenhouse would be modeled after the Texas blackland prairies, with temperatures varying from 35° F to 95° F and having a yearly rainfall of about 880 mm (National Weather Service, 2009). The flora of this greenhouse would predominately be big and little bluestem grasses, Indian grass, gamagrass and switchgrass (World Wildlife Fund, 2001).

Experimental Variable: Greenhouse Glazing and Diffuse Radiation

Greenhouse coverings and stratospheric aerosols affect incoming radiation in a similar way. Greenhouse glazing reflects direct radiation and therefore decreases the direct radiation that reaches the plants (Giacomelli, 1993). Like stratospheric aerosol injection, greenhouse glazing also increases diffuse radiation reaching plants (Giacomelli, 1993). The greenhouse covering's effect on incoming radiation is summarized in figure 3. The greenhouse serves as a good analog to model the effect of this geoengineering scheme without physically manipulating the atmosphere.

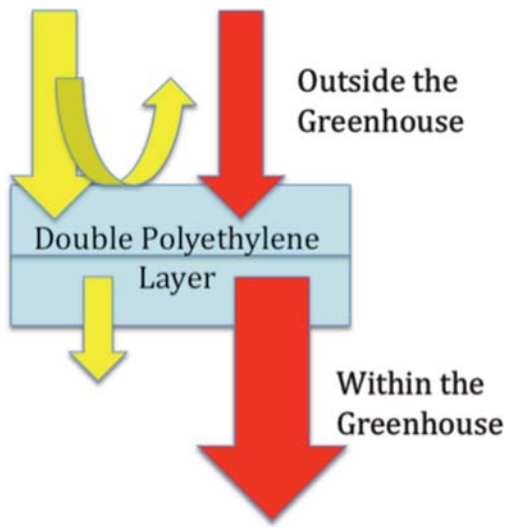

Figure 3 The effect of double polyethylene layer on incoming radiation. The red arrows represent diffuse radiation that is magnified by the glazing. The yellow arrows are direct radiation, some of which is reflected at the surface.

The variable in this experiment is incoming diffuse radiation. Different greenhouse glazing materials will be utilized to manipulate and control the levels of diffuse radiation. To model the natural state the control greenhouse will be constructed of thin glass because this glazing does not manipulate incoming radiation to the extent that other materials do (Giacomelli, 1999). The experiment does not take the control to be the natural environment because there are factors such as predation, variation in nutrients and weather that might not be mimicked within the experimental greenhouse. To learn about the effect of reduced direct radiation and increased diffuse radiation we need to keep all the other factors constant.

The experimental greenhouse at each location will be composed of a double-layered polyethylene glaze. Transmittance (τ) is defined as the ratio between radiation impinging on the greenhouse covering (I_0) and radiation within the greenhouse (**I**) (Giacomelli, 1993). That is,

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Experimentation on double polyethylene glaze has measured its transmittance to be 80% (Giacomelli, 1999). A single layer of polyethylene results in 29% diffusion beneath the glaze while a double layer of polyethylene results in a 40% diffusion (Giacomelli, 1999).

Another factor to consider is the presence of structural support beams. Structural beams can block incoming radiation of certain orientations and create excess shadows. An ideal greenhouse would be one without bulky support beams and certain polyethylene greenhouse coverings do not require structural support. To ensure similarity between the control and experimental greenhouses the same structural supports will be used in both greenhouses.

The constructed greenhouses will be on the order of magnitude of the Eden project greenhouses. A photo of the Eden project greenhouse domes is shown in figure 4. The size of the Mediterranean biome of the Eden project has been chosen for replication in this experiment. The proposed greenhouses will be 30 m high and cover an area of 6540 m^2 ("Mediterranean Biome"). This large size will allow for a more accurate representation of the ecosystem in question than a smaller greenhouse could.

Figure 4 The Eden Project in Cornwall, England. The Eden Project is a tourist attraction that features the largest greenhouses in the world. Ecosystems from around the world are recreated in the biomes. Source: http://botanytcd.files.wordpress.com/2009/09/eden-project.jpg

Measuring Net Primary Productivity

Net primary productivity is defined as the total growth of organic material in a set period of time (Clark, 2001). Therefore, to measure autotrophic productivity we will consider all of the new plant components, including new leaves, branches, seeds, roots, etc. (Clark, 2001).

Within the greenhouse random quadrats will be selected and the change in biomass will be measured and recorded on a monthly basis. The monthly collection of data will include measuring the dry weight by clipping vegetation and also collecting the dead vegetation in the given quadrat ("Estimation of NPP,"). NPP will then be calculated using the equation of Weigert and Evans from 1964 (where r is the rate of decomposition):

$$\text{NPP} = \Sigma\ \Delta\text{Biomass} + \Delta\text{Total Dead} + r\ (\text{Total Dead})$$

This experiment is intended to run continuously for several decades to quantify the long-term responses of terrestrial autotrophs to sulfate aerosol manipulation. The specific duration of experimentation will be dependent on the results of the experiment and whether the results seem worthy of continued study.

Expected Results

Past experiments and studies provide information that allows us to make conjectures about the results of the proposed DRCG experiment. Many predictions of potential effects of injecting sulfur into the stratosphere have relied on the proposed geoengineering scheme's similarity to volcanic eruptions. Lianhung Gu and colleagues have studied the effects of the Mount Pinatubo eruption on Harvard forest (2003). Their experiment examined the effect that increased diffuse radiation, brought about by volcanic eruption, had on Harvard forest's productivity. As shown in figure 2, they found that both diffuse solar radiation and rates of

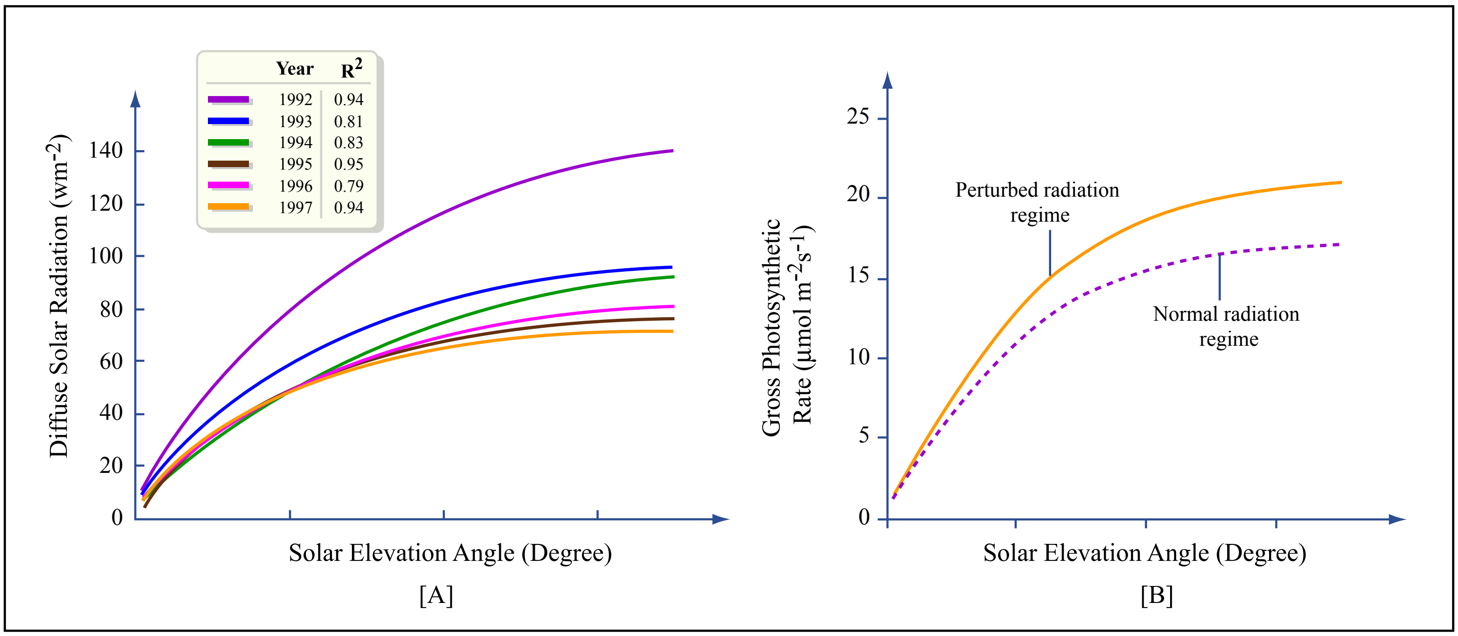

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Figure 2 Effects of the Mount Pinatubo eruption observed at Harvard Forest 2a) Diffuse Solar Radiation vs. Solar Elevation Angle 2b) Gross Photosynthetic Rate vs. Solar Elevation Angle. In the years following the 1991 eruption both diffuse radiation and the rate of photosynthesis increased (Adapted from Gu, 2003).

Injection of sulfur dioxide into the atmosphere by volcanic eruptions is an isolated and infrequent occurrence. However, in order to mitigate global climate change the injection of sulfur into the stratosphere would need to happen continuously for very long periods of time. While the analogy with volcanic eruption might hold at first we do not know if and by how much the effects will deviate from the natural analog upon continuous implementation. We cannot expect all of our concerns and questions to be addressed by studies on volcanic eruptions that lack continuous implementation necessary to mitigate global climate change. Further experimentation that examines the effects of continuous implementation, such as the proposed DRCG experiment, needs to be done in order to better understand the practicality of mitigating global climate change through stratospheric sulfur injection.

The expectation that stratospheric sulfur injection results in increased autotrophic productivity is further supported by agricultural principles established by crop and forest scientists (Gu, 2003). It has been shown that plant canopies have higher photosynthetic efficiencies when using diffuse radiation as opposed to from direct radiation (Gu, 2003). Diffuse radiation reaches plants at many different angles and therefore allows a greater portion of the plant's surface to photosynthesize.

Much attention is often drawn to the negative unintended consequences of geoengineering but I predict this experiment will reveal a positive one; that stratospheric sulfur injection increases net primary productivity. If the experiment does find that alteration of incoming radiation fosters primary productivity we are actually increasing the ability of primary producers to act as carbon sinks. Some geoengineering schemes focus solely on enhancing terrestrial autotrophs' carbon sink potential. Stratospheric sulfur injection may prove to be dually effective in that it creates a cooling effect by decreasing the direct radiation reaching the surface while it also increases terrestrial carbon sink potential and removes carbon dioxide from the atmosphere.

Recommendations and Concluding Discussion

The proposed DRCG experiment focuses on the terrestrial autotroph response to alteration of radiation brought about by the injection of sulfur into the stratosphere. The oceans cover 71% of the Earth's surface and it is therefore very important to investigate the aquatic response to radiation alteration due to stratospheric sulfur injection as well. The aquatic component is out of the scope of the proposed DRCG experiment but it is something that should be investigated to gain a better understanding of the implications of the worldwide implementation of stratospheric sulfur injection.

Stratospheric sulfur injection and geoengineering schemes at large involve the manipulation of the environment on a planetary scale. Yes, we can design experiments to enlighten our understanding of the implications of geoengineering schemes. We may find that some experiments reveal positive unintended consequences while others reveal different negative consequences. Yet, even if we do test the geoengineering scheme in every way that we can fathom there will still remain unrealized and unpredictable side effects. We cannot accurately model our biosphere and all of its complex functions as of now so a complete understanding of geoengineering implications cannot be realized without physical implementation.

Intentionally manipulating the global environment may not be the best idea to mitigate climate change. However, testing geoengineering schemes is important because as other efforts, such as reducing carbon dioxide emissions, continue to fall through geoengineering may be something we are forced to rely on to save our planet. If this worst-case scenario were to arise we would be much better prepared to cope with potential side effects if we had analyzed them to the best of our ability. I have proposed the DRCG experiment for this very reason: to enlighten our understanding of the implications of geoengineering by stratospheric sulfur injection.

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