

Impact of geoengineering schemes on the terrestrial biosphere

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[1] Climate stabilization via “Geoengineering” schemes seek to mitigate climate change due to increased greenhouse gases by compensating reduction in solar radiation incident on earth’s surface. In this paper, we address the impact of these climate stabilization schemes on terrestrial biosphere using equilibrium simulations from a coupled atmosphere-terrestrial biosphere model. Climate stabilization would tend to limit changes in vegetation distribution brought on by climate change, but would not prevent CO₂-induced changes in Net Primary Productivity (NPP) or biomass; indeed, if CO₂ fertilization is significant, then a climate-stabilized world could have higher NPP than our current world. Nevertheless, there are many reasons why geoengineering is not a preferred option for climate stabilization. *INDEX TERMS*: 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 4806 Oceanography: Biological and Chemical: Carbon cycling. *Citation*: Govindasamy, B., S. Thompson, P. B. Duffy, K. Caldeira, and C. Delire, Impact of geoengineering schemes on the terrestrial biosphere, *Geophys. Res. Lett.*, 29(22), 2061, doi:10.1029/2002GL015911, 2002.

1. Introduction

[2] It has been suggested that climate change induced by anthropogenic CO₂ could be cost-effectively counteracted with geoengineering (large scale planetary management) schemes designed to diminish the solar radiation incident on Earth’s surface [Early, 1989; Seifritz, 1989; NAS, 1992; Watson et al., 1995; Flannery et al., 1997; Teller et al., 1997]. Though the spatial and temporal pattern of radiative forcing from greenhouse gases differs from that of sunlight, it was shown in recent studies [Govindasamy and Caldeira, 2000; Govindasamy et al., 2002] that these schemes would largely mitigate regional or seasonal climate change for a doubling and quadrupling of the atmospheric CO₂ content.

[3] A limitation of previous modeling studies is that they did not consider the impact of these geoengineering schemes on the terrestrial biosphere. Terrestrial ecosystems are a critical component of the global carbon cycle. During the 1980s, for example, oceanic and terrestrial uptake of carbon amounted to a quarter to a third of anthropogenic CO₂ emissions with strong interannual variability [Braswell et al., 1997; Prentice et al., 2000, 2001]. A better understanding of carbon balance dynamics is required for interpreting variations in atmosphere-biosphere exchange [Fung

et al., 1997] and for evaluating policies to mitigate anthropogenic CO₂ emissions [United Nations Framework Convention on Climate Change, 1997; IGBP Terrestrial Carbon Working Group, 1998].

[4] In a climate-stabilized world, photosynthesis of plants will be impacted by two competing factors: increased levels of carbon dioxide (the so-called CO₂ fertilization effect) and reduced levels of solar input. It is known that the enhanced physiological effects of CO₂ on productivity and water use efficiency decrease with increasing CO₂ concentration, approaching an asymptote at high CO₂ concentration [King et al., 1997; Cao and Woodward, 1998]. Since the climate remains nearly constant in a climate-stabilized world, a temperature related increase in heterotrophic respiration (an indirect effect of CO₂ increase) is not expected as it is in global warming scenario [Cox et al., 2000; Friedlingstein et al., 2001; Cramer et al., 2001; Joos et al., 2001]. Reduced solar radiation will lead to reduced photosynthetic rate. Therefore, it is not clear *a priori* if the Net Primary Productivity (NPP), biomass and other terrestrial biospheric quantities will increase or decrease in a stabilized climate compared to the present day climate. Also, it is not clear if the predicted change in the distribution of vegetation types due to increasing levels of greenhouse gases could be mitigated by reducing the solar insolation.

[5] In a recent study using an offline vegetation model with climate feedbacks turned off [Wuebbles et al., 2001], it was found that the reduction of incoming solar radiation by 1.8% did not cause significant reduction in NPP. In this study, we address the impact of climate stabilization on terrestrial biosphere using equilibrium simulations from a coupled atmosphere-dynamic vegetation model that includes climate feedbacks. We emphasize that we have performed equilibrium simulations and therefore our simulations can not predict the transient effects of increase in atmospheric CO₂ concentration, climate change and geoengineering on Net Ecosystem Productivity (NEP). Our results are from a single modeling study and validation using other atmospheric and dynamic vegetation models is required.

2. Model

[6] We adopted Version 3 of the atmospheric general circulation model, Community Climate Model (CCM3) developed at the National Center for Atmospheric Research [Kiehl et al., 1996] and coupled it to a terrestrial biosphere model, Integrated Biosphere Simulator or IBIS [Foley et al., 1996; Kucharik et al., 2000]. The horizontal resolution of both models is approximately 2.8° in latitude and 2.8° in longitude. The atmosphere model has 18 levels in the vertical. We adopted a version of CCM3 with a simple slab ocean-thermodynamic sea ice model, which allows for a

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simple interactive surface for the ocean and sea ice components of the climate system.

[7] Land surface biophysics, terrestrial carbon flux and global vegetation dynamics are represented in a single, physically consistent modeling framework within IBIS. IBIS performs a coupled simulation of surface water, energy and carbon fluxes on hourly timesteps and integrates them over the year to estimate annual water and carbon balance. The annual carbon balance of vegetation is used to predict changes in the leaf area index and biomass for each of 12 plant functional types, which compete for light and water using different ecological strategies. IBIS also simulates carbon cycling through litter and soil organic matter. When driven by observed climatological datasets, the model's near-equilibrium runoff, Net Primary Productivity (NPP), and vegetation categories show a fair degree of agreement with observations [Foley *et al.*, 1996; Kucharik, *et al.*, 2000].

3. Experiments

[8] To evaluate the extent to which an effective reduction in solar flux might mitigate the biospheric impacts of increased atmospheric CO₂ content, we performed four model simulations: (i) "Control", with a CO₂ content of 355 ppm and incoming solar flux of 1367 W m⁻²; (ii) "Doubled CO₂", with doubled atmospheric CO₂ content (710 ppm), but the same incoming solar flux as the Control simulation; (iii) "Solar" with a CO₂ content same as control, but solar flux reduced by 1.8 %; and (iv) "Stabilized", with doubled atmospheric CO₂ content and the solar flux reduced by 1.8 %. This reduction in solar luminosity was chosen to approximately offset the radiative forcing from a CO₂ doubling in this model (4.17 W m⁻²), taking into consideration the model's planetary albedo. In practice, this reduction in solar radiation incident on the Earth could be effected through the placement of reflecting or scattering devices between the Earth and Sun [Early, 1989; Flannery *et al.*, 1997; Teller *et al.*, 1997].

[9] For all the experiments, the biosphere model was initialized with a state corresponding to present day conditions. From this initial state, the coupled atmosphere-biosphere model typically needs to run for at least ~75 simulated years so that NPP, NEP, biomass and soil carbon approach quasi-equilibrium. During the spin up period, the soil carbon spin up was accelerated by a factor of 40 in all the experiments. The climate statistics presented below are the averaged values over the last 25 years of model simulations. For the Control and Solar experiments, the model was spun up for 75 years with soil carbon acceleration and total simulated period was 100 years. For the Doubled CO₂ and Stabilized experiments, the spin up period was 100 years and total simulated period was 125 years.

4. Results

[10] The global and annual means of selected variables from the four simulations are listed in Table 1. The climate warms by 2.42 K in the Doubled CO₂ experiment and cools by nearly identical amount in the Solar experiment. Precipitation increases by 3.7% for Doubled CO₂ and decreases by

Table 1. Global and Annual Mean Model Results

Experiment	Surface Temperature Change (K)	Precipitation Change (%)	NPP (Gt-C/yr)	Biomass Gt-C	Heterotrophic Respiration (Gt-C/yr)
Control	0.00	0.0	56.4	631.6	50.1
Doubled CO ₂	2.42	3.7	100.1	1212.9	87.5
Solar	-2.40	-5.8	55.1	619.5	49.9
Stabilized	0.14	-1.7	97.1	1156.2	84.7

5.8% in the Solar experiment. In Doubled CO₂ experiment, the biospheric quantities like NPP, and biomass almost double in response to increased availability of CO₂ suggesting a strong response of the biosphere to CO₂. That this response is largely due to CO₂ is confirmed by comparing NPP in the Control to Stabilized. Heterotrophic respiration also increases because of the increase in the soil carbon pool. Terrestrial disturbances which are prescribed in this model account for the difference between NPP and heterotrophic respiration in IBIS. Our results from Doubled CO₂ experiment are in fairly close agreement with previous results from six dynamic vegetation models run offline [Cramer *et al.*, 2001]. Biospheric quantities in Solar experiment are very close to the control climate experiment suggesting that photosynthesis and respiration of plants are relatively insensitive to small reductions in sunlight in this model.

[11] It is clear from Table 1 that the global- and annual-mean climate (e.g., surface temperature and precipitation) of the Stabilized is similar to Control as shown in recent studies [Govindasamy and Caldeira, 2000; Govindasamy *et al.*, 2002]. Nevertheless, there is some residual warming and reduction in precipitation in the Stabilized case. These factors, coupled with diminished solar flux, might be expected to diminish NPP. However, the biospheric quantities in Stabilized are much closer to Doubled CO₂ than to the Control with the fertilization effect of the increased CO₂, rather than climate, dominating the biospheric response [Wuebbles *et al.*, 2001]. The effect of CO₂ fertilization is probably exaggerated in these simulations because we do not consider factors other than limitation by sunlight, water, and carbon dioxide. Inclusion of other factors, such as nitrogen or phosphate limitation would diminish the magnitude, but not the sign, of these effects. These carbon flux quantities in Stabilized are only slightly smaller than in Doubled CO₂. Therefore, our Stabilized experiment is similar to equilibrium conditions of "constant climate" but elevated CO₂ experiments [Cox *et al.*, 2000; Cramer *et al.*, 2001; Friedlingstein *et al.*, 2001].

[12] We use kappa statistics [Monsrred, 1990] to compare maps of vegetation distributions. Kappa takes on a value of 1 with perfect agreement. It has a value close to zero when the agreement is approximately the same as would be expected by chance. A kappa value of 0.47 (fair agreement) is obtained for a comparison of IBIS simulated vegetation and observations [Foley *et al.*, 1996].

[13] Global comparison of vegetation distributions of Stabilized and Control gives a kappa value of 0.66 (good agreement), a value higher than 0.52 (fair) obtained for Doubled CO₂ and Control (Table 2). Therefore, climate stabilization tends to limit changes in vegetation distribution. Global comparison of Solar and Control gives a kappa value of 0.62 (good agreement), again a value higher than

Table 2. Kappa Statistics: Values of Kappa for Comparison Between Vegetation Distributions From Control, Doubled CO₂, Solar and Stabilized Simulations

	Control	Doubled CO ₂	Solar	Stabilized
Control	1	0.52	0.62	0.66
Doubled CO ₂	0.52	1	0.40	0.66
Solar	0.62	0.40	1	0.51
Stabilized	0.66	0.66	0.51	1

0.52 (fair) obtained for Doubled CO₂ and Control. Therefore, the reduction of solar input has less impact on the vegetation distribution than an equivalent (in terms of climate forcing) increase in atmospheric CO₂.

[14] The first column (or row) of Table 2 can be used to assess the relative sensitivity of vegetation distribution to changes in CO₂ versus changes in climate achieved via changing solar flux. The kappa value of 0.62 obtained from comparing the Control and Solar cases results from changing climate alone. A slightly larger kappa value of 0.66 obtained from comparing Control and Stabilized cases measures the sensitivity of vegetation distribution to changing CO₂ while leaving the climate unchanged to first order. Therefore, the vegetation distribution is slightly more sensitive to changing climate alone than to changing CO₂ concentration alone [Cramer *et al.*, 2001]. This contrasts with our findings for biomass and NPP, which are more sensitive to changes in CO₂ than to changes in climate. These findings are consistent with our expectation that vegetation distribution is controlled nearly equally by climate and CO₂, while biomass is controlled mainly by CO₂ concentration. Kappa values are lower (0.52 and 0.51)

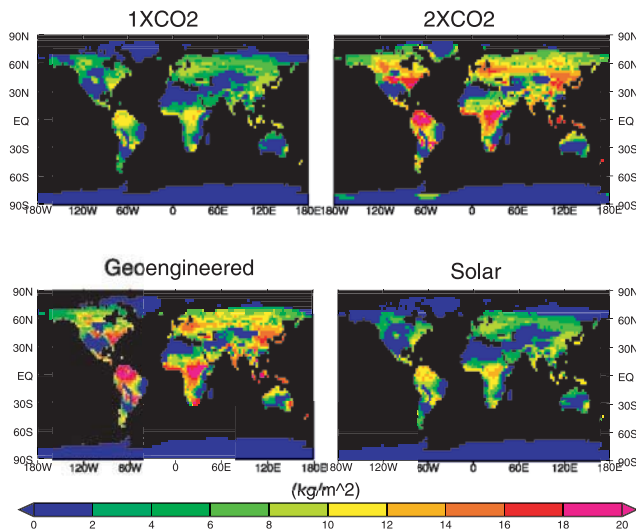


Figure 1. Total annual mean biomass simulated by IBIS in Control, Doubled CO₂, Stabilized and Solar experiments. The spatial patterns are similar in all cases. The magnitudes in Stabilized and Solar are closer to Doubled CO₂ and Control respectively, suggesting strong influence of CO₂ and weak influence of sunlight. The model considers limitation by only light, water, and carbon dioxide. Consideration of nitrogen and phosphate limitation would diminish the magnitude, but not alter the sign, of the response of the model to increased atmospheric CO₂ content.

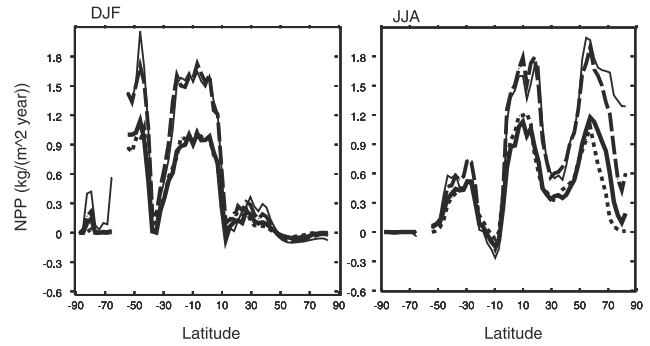


Figure 2. Zonal mean NPP for Control (thick solid) Doubled CO₂ (thin solid), Stabilized (dashed line), and Solar (dotted line) cases for December, January, and February (DJF), and June, July, and August (JJA). The magnitudes in Stabilized and Solar are closer to Doubled CO₂ and Control respectively, suggesting strong influence of CO₂ and weak influence of sunlight.

when both climate and CO₂ have changed (comparison of Control and Doubled CO₂, and, Solar and Stabilized). Kappa is only 0.40 (poor agreement) for larger climate change (comparison of Doubled CO₂ and Solar) which confirms the dependence of vegetation distribution on climate.

[15] Simulated annual mean biomass for the four cases are shown in Figure 1. Regions of highest biomass are associated with warm and moist climates and areas of low or zero biomass are in the extreme subtropical deserts, high-altitude areas and polar latitudes. The spatial patterns are similar in all cases with correlation exceeding 90% between any two cases (Figure 1). With the exception of the boreal regions where light is a limiting factor for plant growth, the magnitude of biomass is similar in Control and Solar cases, indicating negligible influence of slight reduction in sunlight on NPP and biomass. Similarly, the magnitudes are similar in Doubled CO₂ and Stabilized cases, confirming the relatively weak influence of solar flux and strong influence of CO₂ on terrestrial biological activity in our simulations. Maps of other quantities such as NPP, leaf area index, heterotrophic respiration, and soil carbon exhibit similar characteristics.

[16] Zonal mean NPP exhibit greater sensitivity in the summer hemispheres and tropics (Figure 2). Latitudinal distribution of NPP is similar in Doubled CO₂ and Stabilized simulations except in Northern Hemisphere high latitudes during JJA (Figure 2). In the Stabilized case, the increase relative to Control is slightly less than in Doubled CO₂, because the climate is cooler and drier than the Doubled CO₂ case. The latitudinal distribution is nearly the same in Control and Solar. In the northern high latitudes where light is a limiting factor for plant growth, the sun light reduced Solar results in decreased NPP relative to Control.

5. Discussion

[17] Our results suggest that changes in solar flux and atmospheric CO₂ content may be considered to be roughly additive and independent in terms of their effects on NPP.

The 1.8% reduction in solar flux reduces NPP by about 2.4% starting from the Control simulation, and about 3.0% starting from the Doubled-CO₂ simulation (Table 1). However, in this model doubling CO₂ increases NPP by 77% relative to the Control case and 76% relative to the Solar case. The Stabilized case has an NPP 72% higher than the Control case. In the real world, as opposed to our model, CO₂-fertilized ecosystems may run into nutrient limitations, which would diminish the magnitude, but not the sign of the CO₂ fertilization effect. Our results indicate that a climate-stabilized world could have higher NPP than our current world. However, climate stabilization might prevent some changes in vegetation distribution due to climate change but would have little effectiveness in preventing changes in NPP and biomass.

[18] The high sensitivity of our terrestrial biosphere model to CO₂ is due to two reasons. First, we prescribed the atmospheric CO₂ concentration, providing in effect a infinite reservoir of CO₂; feedbacks from biospheric changes to CO₂ in the atmosphere were not included. Second, there is no nitrogen limitation in our biosphere model. Changes in nitrogen availability are important to the carbon cycle through changes in plant nutrient availability [Schimel, 1998; Nadelhoffer et al., 1999]. Models that include nitrogen limitation show less sensitivity of CO₂ fluxes for changes in atmospheric CO₂ [Cramer et al., 2001].

[19] Caution should be exercised in interpreting our results because we have used *single* atmospheric general circulation model coupled to a mixed layer ocean model. Our model lacks a sophisticated ocean model, and atmospheric CO₂ is prescribed. It also lacks the feedbacks associated with ocean biosphere. Other atmospheric GCMs coupled to a full, three dimensional ocean and fully interactive carbon models and subjected to transient forcing would likely yield quantitatively different results. Nonetheless, we believe that the basic result that climate stabilization would do little to maintain the present terrestrial biosphere is most likely model independent.

[20] There are many reasons not to engage in geoengineering schemes for climate stabilization. Obviously, our model is much simpler than the real world, and in the real world geoengineering could have unforeseen consequences not anticipated by our model. Even with a stabilized climate, CO₂ fertilization could impact ecosystem goods and services not represented by our terrestrial ecosystem model, such as species abundance and competition, habitat loss, biodiversity and other disturbances [Root and Schneider, 1993]. Some stabilization schemes could adversely impact the ozone layer. It would be difficult to develop and maintain over centuries an international consensus to engage in a large-scale geoengineering project [Schneider, 2001]. Failure of a stabilization scheme could be catastrophic. Furthermore, there are a host of ethical problems associated with geoengineering Earth's climate.

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