

## Quantifying the effects of CO<sub>2</sub>-fertilized vegetation on future global climate and carbon dynamics

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[1] Climate and the global carbon cycle are a tightly coupled system where changes in climate affect exchange of atmospheric CO<sub>2</sub> with the land biosphere and the ocean, and vice-versa. In particular, the response of the land biosphere to the ongoing increase in atmospheric CO<sub>2</sub> is not well understood. To evaluate the approximate upper and lower limits of land carbon uptake, we perform simulations using a comprehensive climate-carbon model. In one case the land biosphere is vigorously fertilized by added CO<sub>2</sub> and sequesters carbon throughout the 21st century. In a second case, CO<sub>2</sub> fertilization saturates in year 2000; here the land becomes an additional source of CO<sub>2</sub> by 2050. The predicted atmospheric CO<sub>2</sub> concentration at year 2100 differs by 40% between the two cases. We show that current uncertainties preclude determination of whether the land biosphere will amplify or damp atmospheric CO<sub>2</sub> increases by the end of the century. *INDEX TERMS*: 0315

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### 1. Introduction

[2] The magnitudes of feedbacks within the climate-carbon system are poorly constrained. Higher CO<sub>2</sub> concentrations increase photosynthesis and promote water-use and nitrogen-use efficiency of plants, ultimately increasing plant growth [Houghton *et al.*, 2001]. Biomass and soil carbon, and thus terrestrial carbon uptake, may be expected to increase with higher atmospheric CO<sub>2</sub> levels. However, the effects of photosynthetic CO<sub>2</sub> “fertilization” will saturate at sufficiently high CO<sub>2</sub> levels [Farquhar *et al.*, 1980; Houghton *et al.*, 2001], and higher global temperatures may increase the loss of soil carbon to the atmosphere [Giardina and Ryan, 2000; Houghton *et al.*, 2001; Lloyd and Taylor, 1994].

[3] Results from two recent modeling studies, referred to here as Hadley [Cox *et al.*, 2000] and IPSL [Friedlingstein *et al.*, 2001], led to different conclusions regarding the role of the land biosphere in future global change. In the Hadley simulation, the land biosphere becomes a net source of CO<sub>2</sub> to the atmosphere by year 2050, whereas in the IPSL simulation, it remains a net sink throughout the 21st century. We show that we can produce a change of sign in biospheric response by changing only one assumption in a fully coupled three-dimensional model: whether CO<sub>2</sub>-fertilization rapidly saturates in terrestrial ecosystems. Other factors, such as climate change, land-use change, fire suppression, and N-fertilization could also potentially affect the sign of terrestrial carbon uptake.

[4] Higher atmospheric CO<sub>2</sub> concentration stimulates leaf-photosynthesis and favors more efficient use of available water [Owensby *et al.*, 1999]. Models incorporating this dynamic without nutrient constraints to growth tend to be more sensitive to CO<sub>2</sub> fertilization [Cramer *et al.*, 2001; Kicklighter *et al.*, 1999]. However, in real ecosystems, limited availability of nutrients or long-term acclimation responses may diminish the sensitivity to added CO<sub>2</sub> [Hungate *et al.*, 2003; Nadelhoffer *et al.*, 1999; Shaw *et al.*, 2002; Schimel, 1998].

### 2. Coupled Climate/Carbon Model

[5] To investigate the dynamics of the land biosphere in the coupled climatic system, we coupled the ocean-atmosphere climate model PCTM [Meehl *et al.*, 2004; Washington *et al.*, 2000] to the IBIS2 terrestrial biosphere model [Foley *et al.*, 1996; Kucharik *et al.*, 2000] and a modified version of the OCMIP ocean biogeochemistry model protocol (R. G. Najjar and J. C. Orr, unpublished manuscript, 1999) (see <http://www.ipsl.jussieu.fr/OCMIP/phase2/simulations/Biotic/HOWTO-Biotic.html>). The horizontal resolutions of the atmosphere and ocean circulation model grids are approximately 280 km and 70 km, respectively. IBIS2 simulates canopy physiology, plant phenology, vegetation dynamics and carbon cycling. The ocean biogeochemistry model predicts air-sea CO<sub>2</sub> fluxes, biogenic export of organic matter and calcium carbonate, and distributions of dissolved inorganic carbon, phosphate, oxygen, alkalinity, and dissolved organic matter. We replaced the OCMIP export formulation with a formulation based on that of Maier-Reimer [1993].

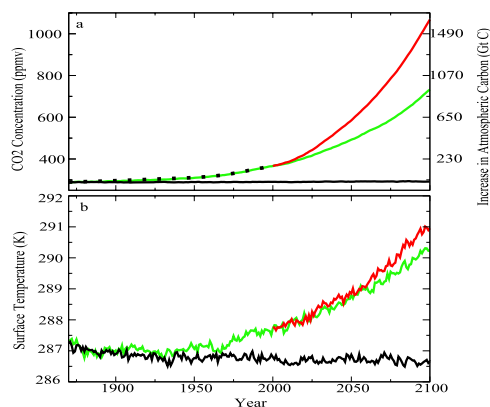
[6] In the LLNL PCTM-IBIS2-OCMIP system, precipitation biases typical of climate models can cause vegetation errors that, in turn, amplify precipitation biases. This erroneous feedback results in unacceptable vegetation in some areas, particularly parts of the Amazon. To remedy this, at

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**Figure 1.** Simulated atmospheric CO<sub>2</sub> and global mean surface temperature from 1870 to 2100. (a) CO<sub>2</sub> for the control (black), fertilization (green), and saturation (red) cases. Black dots are observed CO<sub>2</sub> concentrations. If CO<sub>2</sub> fertilization saturates early, the land-biosphere becomes a net source of CO<sub>2</sub> to the atmosphere, adding to anthropogenic CO<sub>2</sub> emissions. (b) Temperature for the same cases as (a).

every surface grid cell and time step the precipitation field is multiplied by a correction field that is a function of position, but otherwise static and identical across all runs. We further scale the precipitation field so as to maintain the global conservation of water. This correction procedure spatially redistributes the model's present-day annual mean precipitation towards observed means.

### 3. Experiments

[7] We integrate the fully coupled model to quasi-equilibrium to form a year 1870 pre-industrial initial condition that is used as the starting point for three model cases. The “control” case has no CO<sub>2</sub> emissions and thus no change in radiative forcing for the period 1870–2100. Model drift for the control case over years 1900 to 2100 is  $-0.35$  K in mean surface temperature and  $+3.14$  ppmv in atmospheric CO<sub>2</sub>. Both are minimal residuals from an imbalance in the initial state and are not subtracted from the other simulations in our analysis.

[8] The “fertilization” case has CO<sub>2</sub> emissions specified at historical levels [Marland *et al.*, 2000] for 1870–2000 and according to the IPCC scenario [Houghton *et al.*, 2001] SRES A2 from 2000–2100. Non-CO<sub>2</sub> greenhouse gas concentrations are specified at historical levels for 1870–2000 and SRES A2 levels from 2000–2100. Land use emissions are reconstructions [Houghton, 2003] for the historical period and from the SRES A2 scenario thereafter. In this scenario, total emissions reach 29 Gigatons carbon (GtC) per year in year 2100 from present day values of 8 GtC per year.

[9] The “saturation” case is identical to the fertilization case except the CO<sub>2</sub> fertilization is assumed to saturate at the year 2000 concentration, accomplished by forcing the terrestrial biosphere model with a constant CO<sub>2</sub> concentration of 366 ppmv after year 2000. Because the terrestrial biosphere model that we use is highly responsive to CO<sub>2</sub> fertilization [Cramer *et al.*, 2001], the fertilization case approximates an upper limit to the land uptake of carbon

assuming unlimited nitrogen/nutrient availability. Capping all fertilization at its year 2000 value in the saturation case will approximate a strongly nitrogen/nutrient limited system.

### 4. Results

[10] Figure 1a shows that assumptions regarding CO<sub>2</sub>-fertilization of the land biosphere greatly affect the atmospheric concentration of CO<sub>2</sub>. Year 2100 atmospheric CO<sub>2</sub> concentrations are 336 ppmv higher in the saturation case than in the fertilization case. In the SRES A2 scenario, 1790 GtC is emitted to the atmosphere over the 21st century; atmospheric CO<sub>2</sub> content increases by 776 GtC (366 ppmv) and 1489 GtC (702 ppmv) in our fertilization and saturation cases, respectively.

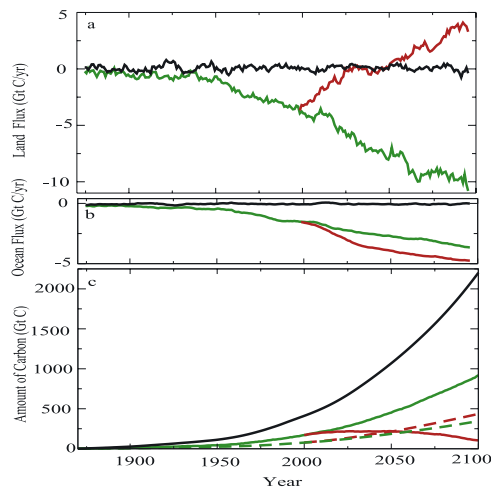
[11] The global climate-carbon feedback factor is a useful system metric defined as the ratio of CO<sub>2</sub> change when climate is changing, to the CO<sub>2</sub> change when climate is constant [Friedlingstein *et al.*, 2003]. We perform an additional constant-climate simulation with full emissions to obtain a feedback factor of 1.13 for our fertilization case. The feedback factors for similar fertilization simulations are 1.19 for IPSL [Friedlingstein *et al.*, 2001] and 1.68 for Hadley [Cox *et al.*, 2000]. Therefore, our model shows the weakest positive feedback between climate and the carbon cycle of the current published results for fertilization cases. Note, however, that our feedback factor increases to 2.05 in our saturation case. This is an indication of the uncertainty in quantifying the climate-carbon cycle feedback, arising from a single model assumption.

[12] The temperature difference at year 2100 between the saturation and fertilization cases is only 0.7 K (Figure 1b), but it should be noted that the climatic system has large thermal inertia due to the large heat capacity of the oceans. If the simulations were run to equilibrium with the year 2100 CO<sub>2</sub> values, the temperature difference would be approximately 1.1 K (estimated from the model's equilibrium climate sensitivity of 2.1 K per doubling of CO<sub>2</sub>).

[13] Results (Figure 2a) show that assumptions regarding the saturation of CO<sub>2</sub>-fertilization can affect the sign of the CO<sub>2</sub> flux between the atmosphere and land by century's end. Direct CO<sub>2</sub> effects are expected to lead to increased terrestrial carbon uptake, but temperature effects can lead to increased heterotrophic respiration and loss of soil carbon [Cox *et al.*, 2000; Cramer *et al.*, 2001; Friedlingstein *et al.*, 2001; Joos *et al.*, 2001], at least until a possible acclimation of soil microbiology to the higher temperatures [Kirschbaum, 2000; Tjoelker *et al.*, 2001]. In the saturation case, by year 2100 the land-biosphere has become a net source of CO<sub>2</sub> to the atmosphere, as temperature effects dominate CO<sub>2</sub>-fertilization effects. In the fertilization case, CO<sub>2</sub>-fertilization effects dominate temperature effects, resulting in continued net biospheric growth.

[14] In contrast to Hadley [Cox *et al.*, 2000], but in agreement with IPSL [Friedlingstein *et al.*, 2001], our land carbon cycle does not become a net source of carbon to the atmosphere in the fertilization case. A loss of vegetation biomass does not occur in either of our simulations (but soil carbon does decline by year 2100 in our saturation case).

[15] The model's historical ocean carbon uptake of 77 GtC is an underestimate when compared against the recent observational estimates of 118 GtC for the period



**Figure 2.** Global carbon fluxes and carbon inventory change from 1870 to 2100. (a) Flux of carbon from land to atmosphere. Control (black), fertilization (green), and saturation (red) cases. In the saturation case the land becomes a net source of carbon by year 2050. (b) The same as (a) but for carbon flux from ocean to atmosphere. (c) Global carbon change from the 1870 pre-industrial starting point. Total earth system (black), land (solid), and ocean (dashed). Fertilization case (green), and saturation case (red).

from 1800 to 1994 [Sabine *et al.*, 2004]. Between year 2000 and year 2100, ocean/atmosphere carbon fluxes show significant differences between the fertilization and saturation cases (Figure 2b). Ocean carbon storage increases by 269 and 357 GtC in the two cases (Figure 2c). Ocean uptake is greater in the saturation case because increased atmospheric CO<sub>2</sub> concentrations drive an increased flux of CO<sub>2</sub> from the atmosphere to the ocean that is larger than any counteracting temperature and biogeochemical effects [Sarmiento *et al.*, 1998]. The increase in ocean carbon storage at year 2100 in both the cases is less than 15% of the amount that could be stored if the ocean were in equilibrium with the respective year 2100 atmospheric CO<sub>2</sub> concentrations [Kheshgi, 2004].

[16] Cumulative carbon emissions since 1870 reach 2200 GtC by year 2100 (Figure 2c). In the fertilization case, the land biosphere and the oceans sequester 919 GtC (42%) and 346 GtC (15.5%) of the total emissions, respectively. In the saturation case, the corresponding amounts are 104 GtC (5%) and 435 GtC (19.5%). Thus, in our model the variation in land uptake of carbon due to the degree of CO<sub>2</sub> fertilization varies from 5% to 42% of the total carbon emitted. The carbon remaining in the atmosphere is 935 GtC (42.5%) and 1661 GtC (75.5%) for the fertilization and saturation cases, respectively.

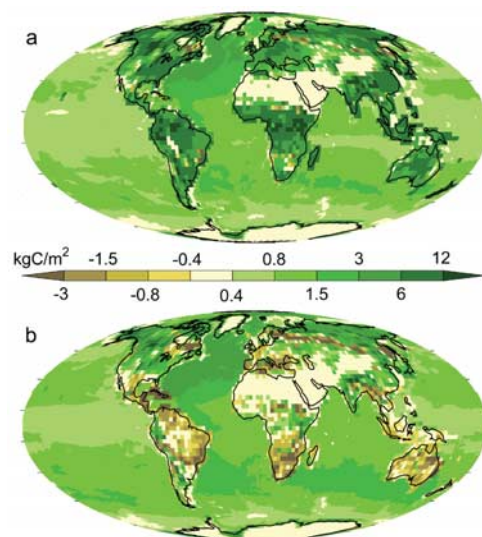
[17] In the fertilization case, the total land ecosystem nitrogen increases by 20 Gt between year 2000 and 2100. This is much larger than estimates [Hungate *et al.*, 2003], indicating only 6 Gt of additional nitrogen could accumulate in the terrestrial biosphere by 2100. In contrast, in the saturation case terrestrial nitrogen declines by 8 Gt during the same period.

[18] The geography of simulated carbon uptake in the fertilization case over the period 1870–2100 (Figure 3a)

shows that anthropogenic carbon is stored on land primarily in areas of high vegetation productivity (Amazonia, central Africa, south and southeast Asia) or relatively slow microbial decomposition (boreal forests). Currents and circulation make storage somewhat more uniform for the ocean, but it is higher in the North Atlantic and Mid-Southern Oceans, which reflects proximity to regions of net CO<sub>2</sub> uptake [Caldeira and Duffy, 2000; Wickett *et al.*, 2003]. In the saturation case (Figure 3b), the oceanic storage increases slightly and carbon is released over many parts of the land area.

## 5. Discussion

[19] Even without nutrient limitations, the enhanced physiological effects of CO<sub>2</sub> on plant growth will saturate at high CO<sub>2</sub> concentration [Cao and Woodward, 1998; Farquhar *et al.*, 1980; Houghton *et al.*, 2001]. However, respiration rates would be expected to continue to increase with further CO<sub>2</sub>-induced warming; thus, at some level of atmospheric CO<sub>2</sub>, the land would be expected to become a net CO<sub>2</sub> source. Questions remain when this would occur, and whether it would occur before fossil fuel resources are fully exploited. The climate model used here has an equilibrium climate sensitivity that is at the lower end of the range of the general model population [Houghton *et al.*, 2001]. A more sensitive climate model would increase the amount of warming, increasing heterotrophic respiratory carbon fluxes from soils even more. Hence, high climate sensitivity is more likely to amplify carbon losses from the



**Figure 3.** The simulated geography of carbon stored in the earth system over the period from 1870 to 2100 in the a) fertilization and b) saturation cases (column integrated carbon in kg C/m<sup>2</sup>). Anthropogenic carbon is stored primarily in areas of high vegetation productivity and/or cooler climates over land. Owing to currents, storage is somewhat more uniform for the oceans but higher in the North Atlantic and Mid-Southern oceans, which reflects proximity to regions of net CO<sub>2</sub> uptake. In the saturation case, the oceanic storage increases slightly and carbon is released over many parts of the land area.

land biosphere; a low climate-sensitivity is more likely to allow the land biosphere to damp the climate effects of CO<sub>2</sub> emissions, with carbon uptake by the biosphere dominated by CO<sub>2</sub> fertilization.

[20] For the range of CO<sub>2</sub> fertilization considered in this study, the sign of the net flux of carbon between the atmosphere and land biosphere changes by the end of this century. It is possible that CO<sub>2</sub>-fertilization is weaker (or stronger) than in our simulations, and thus the shift of the land biosphere from a net atmospheric CO<sub>2</sub> sink to net atmospheric CO<sub>2</sub> source could occur earlier (or later) than simulated here.

[21] The choice of year 2000 for the saturation level is artificial; it is driven by the need to have the model reproduce the past evolution of atmospheric CO<sub>2</sub>. The processes responsible for the observed land uptake are uncertain. A standard hypothesis uses the CO<sub>2</sub>-fertilization effect, represented by our fertilization case. The observed uptake could be due to other processes such as change in land use, N-fertilization and fire suppression [Pacala et al., 2001; Schimel et al., 2001]. This is represented by our saturation case where the uptake is, for practical reason only, driven by the atmospheric CO<sub>2</sub> for the historical period. The behavior of CO<sub>2</sub>-fertilization and other processes in the future is uncertain.

[22] The results show that the amount of anthropogenic CO<sub>2</sub> in the atmosphere at the end of the century will probably be sensitive to carbon-cycle processes about which we are uncertain at present. Right now, the uncertain response of the land biosphere to increased CO<sub>2</sub> and climate change prevents us from knowing if terrestrial carbon-cycle feedbacks will damp or amplify global warming.

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