Quantifying the negative feedback of vegetation to greenhouse warming: A modeling approach

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Several climate models indicate that in a 2 × CO2 environment, temperature and precipitation would increase and runoff would increase faster than precipitation. These models, however, did not allow the vegetation to increase its leaf density as a response to the physiological effects of increased CO2 and consequent changes in climate. Other assessments included these interactions but did not account for the vegetation down-regulation to reduce plant’s photosynthetic activity and as such resulted in a weak vegetation negative response. When we combine these interactions in climate simulations with 2 × CO2, the associated increase in precipitation contributes primarily to increase evapotranspiration rather than surface runoff, consistent with observations, and results in an additional cooling effect not fully accounted for in previous simulations with elevated CO2. By accelerating the water cycle, this feedback slows but does not alleviate the projected warming, reducing the land surface warming by 0.6°C. Compared to previous studies, these results imply that long term negative feedback from CO2-induced increases in vegetation density could reduce temperature following a stabilization of CO2 concentration. Citation: Bounoua, L., F. G. Hall, P. J. Sellers, A. Kumar, G. J. Collatz, C. J. Tucker, and M. L. Imhoff (2010), Quantifying the negative feedback of vegetation to greenhouse warming: A modeling approach, Geophys. Res. Lett., 37, L23701, doi:10.1029/2010GL045338.

1. Introduction

A compilation of results from climate models of varying complexity indicates that in a 2 × CO2 environment, temperature would increase between 2 and 4.5°C, and rainfall would increase in most regions except the Mediterranean, the southwestern part of the United States, South Africa and Southwest Asia [Intergovernmental Panel on Climate Change (IPCC), 2007]. Results from these models also indicate that compared to their respective baselines, the global mean surface runoff would increase faster (8.9%) than precipitation (5%) [Nohara et al., 2006]. These assessments, however, did not allow vegetation leaf area index (LAI) to increase with CO2 and subsequent changes in climate. Increase in LAI affects photosynthesis, evapotranspiration, surface albedo and surface roughness, all of which feedback on climate.

Projected increases in global temperature and land precipitation are supported by observations [IPCC, 2001; Wentz et al., 2007]. An increase in land precipitation could also increase soil moisture; and where vegetation growth has been previously water-limited, LAI will increase. Where this happens, evapotranspiration will also increase, leading to a slower rate of atmospheric warming than that projected in the absence of vegetation feedback. Hence, including this feedback in climate simulations with elevated CO2 may reduce the projected warming [Betts et al., 1997].

Observational studies based on long-term records show consistent trends between vegetation and precipitation increase over the Sahel [Anyamba and Tucker, 2005] and relate the increase in vegetation density over North America to change in temperature [Neigh et al., 2008]. Figure 1 shows observational evidence of the quasi-linear relationship between continental-scale vegetation density [Tucker et al., 2005] and the precipitation minus runoff [U.S. Geological Survey, 2007] over the common period of 1982–1995.

Consistent with observations, modeling studies [Piao et al., 2006] indicate that increases in atmospheric CO2, temperature and precipitation account for 49%, 31%, and 13% of the increase in growing season LAI, respectively. They also show that in cold Siberian regions, vegetation growth is associated with temperature increase, while in central North America it is primarily due to increase in precipitation. These modeling studies suggest that the rate of change of LAI with temperature accelerates with increasing soil moisture, but slows down, and even becomes negative, as the mean temperature increases, implying that the current greening trend may weaken or even disappear under continued warming.

Since the pioneering work of Dickinson and Wilson [1986] and Sellers et al. [1986] several models incorporated interactive vegetation. However, these interactive vegetation models are still characterized by large uncertainties and significant divergences in their results [Priedingstein et al., 2006]. Previous work by Betts et al. [1997] and Levis et al. [2000] simulated large scale vegetation feedbacks on elevated CO2-climate by allowing the vegetation to increase its LAI as a response to the physiological effects of increased CO2 and consequent changes in climate. Both of these studies used interactive vegetation-climate models; however neither considered down-regulation as a possible mechanism to reduce plant’s photosynthetic activity under 2 × CO2. Under elevated CO2 plants exhibit some down-regulation characterized by a reduction in the initial CO2-enhanced rates of photosynthesis that result from a gradual decrease in the activity and/or amount of Rubiscos Vmax [Leakey et al., 2000].
[61x582]greenhouse warming. [61x593]approach to quantify the negative feedback of vegetation to –1995 period. [61x703]logical effects simulated in previous and our own RP –beyond the reduction caused by the radiative and physio- [61x681]water availability which is diverted, as an additional effect, to [61x692]scenarios [CO2 environment by requiring the physiological model to –accounts for down [61x440]tion response and may have implications for climate. [61x451]ously suggested. This feedback results in a stronger vegeta- [61x462]tion to increase its foliage as a response to CO2 fertilization [Betts et al., 1997; Levis et al., 2000] and water availability (Figure 2). The RPVB simulation was identical to the RPV simulation; however down-regulation led to increased water availability which was diverted to increasing LAI. Additionally, we used the reduction in Vmax from the RPV-case to increase LAI such that total Vmax within each grid cell approached that of the RP-case (Text S1 of the auxiliary material).1 In SiB2, increases in LAI not only affect the carbon uptake, transpiration and interception rates, but also alter surface albedo and roughness and so affect the exchanges of carbon, energy, water and momentum at the land-atmosphere interface. Furthermore, the model’s vegetation physiological growing season is controlled by low-temperature stress levels below which photosynthesis is inhibited. As temperatures increase with CO2, these stress levels become less severe earlier during the onset of vegetation greening and later during the dormancy phase, increasing thus the length of the growing season. [15] The three simulations start with 2 × CO2 corre- sponding to a stabilization level, and are run long enough to equilibrium. In the real world, the actual timing of when 2 × CO2 could be reached depends on different factors, including emission scenarios. 

3. Results and Discussion
[16] All simulations started from the same initial conditions and are carried out 30 years forward. RP, RPV and RPVB were compared to a Control simulation (C) using 350 ppm for both the radiative and physiological modules of the coupled model. All results are averages from the last 10 years of each simulation. [17] In line with Bonan [1997] and Levis et al. [2000], in the RPVB-case the largest albedo decreases of 6% and 7% occurred over the continents, north of 57.6°N, during winter and spring respectively, due to the masking of snow by photosynthesis through the maximum Rubisco capacity – Vmax, which leads to an increase in the vegetation’s water use efficiency and a relative decrease in evapotranspiration. Since the study of Sellers et al. [1996], other researchers have examined the effect of CO2-induced stomatal closure on the hydrological cycle and have reported similar results [Gedney et al., 2006; Betts et al., 2007].

Figure 2. LAI increase for the RPVB-Control. Eastern U.S region is defined east of the Mississippi.


1Auxiliary materials are available in the HTML. doi:10.1029/2010GL045338.
denser vegetation. On an annual basis, albedo decreased 5% in these latitudes. This is a significant reduction considering that in the RPVB-case the vegetation was not allowed to migrate with climate change; however it is smaller than the change simulated by Levis et al. [2000] where vegetation increased in extent and density. Globally and annually averaged, the albedo effect was relatively small and was dominated by the evaporative effect for an overall net cooling, in agreement with Betts et al. [1997].

Compared to the control, the RP-case produced a carbon uptake increase of 44.6 Pg (1Pg = 10^{15}g). This increase was reduced in the RPV-scenario where the carbon uptake was only 13.4 Pg more than the control (C). As expected, the increase in LAI simulated in the RPVB-case led to a carbon uptake increase close to that simulated under the RP-scenario and is well within the constraints of nitrogen availability reported by Hungate [2003]. This highlights the competing effects of down-regulation and increased LAI on photosynthesis since both the RP and RPVB-cases operated under 2 × CO₂. Compared to RP, the RPVB-simulation resulted in 40% more carbon uptake over the continental U.S while it increased by only 25% over the less water-limited forested area of the eastern U.S, east of the Mississippi (Table 1). This increase in the net carbon uptake is also associated with an increase in evapotranspiration and a cooling of the atmosphere (Figure 3).

The RPVB vegetation-climate feedback led to a projected warming much less than previously simulated due to the increase in evapotranspiration. Globally, the RP-case temperature increased 1.94°C, at the lower end of the 2.0 to 4.5°C range projected by the IPCC [IPCC, 2007] while in

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>RP-C</th>
<th>RPV-C</th>
<th>RPVB-C</th>
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<tbody>
<tr>
<td>All Land</td>
<td>124.80</td>
<td>44.60</td>
<td>13.40</td>
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<td>11.17</td>
<td>4.90</td>
<td>1.75</td>
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<td>Eastern USA</td>
<td>7.23</td>
<td>3.13</td>
<td>1.32</td>
<td>3.92</td>
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</table>

**Table 1.** Carbon Uptake (Pg/yr): Control (C) and Differences From the Control

**Figure 3.** Annual differences of (top) canopy evaporation (Wm⁻²), (middle) leaf area index (m²m⁻²) and (low) surface temperature (°C) between the RPVB and RPV cases (RPVB-RPV). Differences are obtained from averages from last 10-years of simulations at 7.2° × 9° and smoothed for plotting purpose.
Table 2. Surface Temperature (°C): Control (C) and Differences From the Control

<table>
<thead>
<tr>
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<th>RPVB-C</th>
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<td>Global</td>
<td>18.53a</td>
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<tr>
<td>All Land</td>
<td>19.55*</td>
<td>2.80*</td>
<td>2.67*</td>
<td>2.23*</td>
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<tr>
<td>Eastern USA</td>
<td>19.93*</td>
<td>2.92*</td>
<td>2.67*</td>
<td>1.38*</td>
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*Significant at 95% (T-test).

Table 3a. Precipitation (mm.day⁻¹): Control (C) and Relative Differences From the Control (%)

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<th>RPV-C</th>
<th>RPVB-C</th>
</tr>
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<tbody>
<tr>
<td>Global</td>
<td>2.88</td>
<td>4.70(0.135)b</td>
<td>3.0(0.110)b</td>
<td>4.20(0.120)b</td>
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<tr>
<td>All Land</td>
<td>2.75</td>
<td>6.4(0.175)b</td>
<td>3.0(0.082)b</td>
<td>4.3(0.119)b</td>
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<td>Eastern USA</td>
<td>2.36</td>
<td>31.2(0.735)b</td>
<td>10.4(0.246)b</td>
<td>35.7(0.843)b</td>
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*Values in parenthesis are absolute differences from the control.

Table 3b. Same as Table 3a Except for Surface Runoff (mm.day⁻¹)

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<tr>
<th></th>
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<th>RP-C</th>
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<tr>
<td>All Land</td>
<td>1.15</td>
<td>9.8(0.113)c</td>
<td>6.7(0.077)c</td>
<td>4.0(0.046)c</td>
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<tr>
<td>Eastern USA</td>
<td>1.6</td>
<td>35.4(0.567)c</td>
<td>10.9(0.174)c</td>
<td>34.6(0.554)c</td>
</tr>
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*Significant at 95% (T-test).
feedback on warming from increases in LAI than previously suggested. In sharp contrast to previous studies, the feedback also results in precipitation and runoff trends that are consistent with observations [Jackson et al., 2005]. Globally, precipitation increased faster than runoff, especially in forested areas. Most importantly, results from this study suggest that long term negative feedbacks from increases in LAI could act to reduce temperature for years following a stabilization of atmospheric CO₂ concentration.

[26] Acknowledgment. We thank R. Betts for his insightful remarks. The work was partially supported by the NASA’s LCLUC-program.

References


