

## The role of biospheric feedbacks in the simulation of the impact of historical land cover change on the Australian January climate

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[1] Increasing carbon dioxide (CO<sub>2</sub>) concentrations affect vegetation physiologically (through stomatal conductance) and structurally (through changes in leaf area index). It may be important to include these biospheric feedbacks in experiments that explore atmosphere-surface interactions including the impact of historical land cover change (LCC) within the climate system. In this paper, we show that the biospheric feedback affects the simulation of historical human-induced LCC over Australia for January. The biospheric feedbacks reduce the simulated impact of LCC on latent heat flux and temperature. Further, we show that the magnitude of these feedbacks is non-negligible and can be comparable, at regional scales, to changes caused by increases in radiative forcing simulated by a climate model over the same time period. We suggest that exploring the impact of historical LCC, for example on 20th Century climate, without including the biospheric feedbacks may incorrectly assess the impact of LCC. **INDEX TERMS:** 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 1833 Hydrology: Hydroclimatology; 1803 Hydrology: Anthropogenic effects. **Citation:** Narisma, G. T., A. J. Pitman, J. Eastman, I. G. Watterson, R. Pielke Sr., and A. Beltrán-Przekurat, The role of biospheric feedbacks in the simulation of the impact of historical land cover change on the Australian January climate, *Geophys. Res. Lett.*, 30(22), 2168, doi:10.1029/2003GL018261, 2003.

### 1. Introduction

[2] The impact of land cover change (LCC) on climate (defined here as the long-term statistics of weather) has received considerable recent attention, including by the Intergovernmental Panel on Climate Change [Houghton *et al.*, 2001]. Humans have altered a significant fraction of the Earth's surface [Klein Goldewijk, 2001] and this may affect past, present and future climate. Increasing atmospheric CO<sub>2</sub> and the probable changes in temperatures [Houghton *et al.*, 2001] will likely affect vegetation structure and function [Betts *et al.*, 1997], that may then affect the climate system to compound or attenuate the direct impacts of LCC. The physiological and structural response of vegetation to higher CO<sub>2</sub> concentration and temperatures can include reduced stomatal conductance ( $g_s$ ) and increased leaf area index (LAI). The decrease in  $g_s$  tends to decrease the latent heat flux ( $\lambda E$ ) and increase sensible heat, potentially leading to further warming [e.g., Sellers *et al.*, 1996], while the increase in LAI tends to increase  $\lambda E$  and lower temper-

atures. Betts *et al.* [1997] showed that the structural feedback of increasing LAI partially offsets the warming due to a decrease in  $g_s$ .

[3] Experiments that explore the impact of future LCC, with [Bounoua *et al.*, 1999; Levis *et al.*, 2000; Costa and Foley, 2000; Eastman *et al.*, 2001; de Fries *et al.*, 2002] or without biospheric feedbacks [see Table 1 in Costa and Foley, 2000] demonstrate a regional- or global-scale impact of LCC on climate. Some studies incorporate either the physiological feedback [Henderson-Sellers *et al.*, 1995; Sellers *et al.*, 1996] or the structural feedback [Levis and Foley, 1999]. Claussen *et al.* [2001] have explored the vegetation feedback on palaeo-climates while Betts *et al.* [1997, 2000] have focused on future climates. Those experiments that have explored the impact of historical LCC (the last two centuries) have omitted the biospheric feedback [e.g., Chase *et al.*, 2000; Brovkin *et al.*, 1999; Betts, 2001; Zhao and Pitman, 2002]. We explore the consequences of this omission, focusing on the impact of historical LCC on the Australian climate. Narisma and Pitman [2003] showed that historical LCC, without changes in CO<sub>2</sub> or climate and excluding biospheric feedbacks, can affect Australia's climate significantly, perhaps explaining a significant fraction of observed warming. This paper investigates whether including the biospheric feedback in historical LCC experiments affects these conclusions. We explore the impact of this biospheric feedback on temperature and latent heat flux, but do not account for the impact of the physiological or structural responses on atmospheric CO<sub>2</sub>. We quantify the size of the biospheric feedback by assessing the impact of LCC on climate simulated with and without the physiological and structural response of the biosphere in Australia to changes in climate and CO<sub>2</sub>. We then discuss the implications of including these feedbacks in historical LCC simulations.

### 2. Experimental Methods

[4] We used the Colorado State University Regional Atmospheric Modeling System (RAMS) [Pielke *et al.*, 1992] coupled to the General Energy and Mass Transport Model (GEMTM) [Eastman *et al.*, 2001]. GEMTM is a dynamic plant model that allows the vegetation to respond to changes in CO<sub>2</sub> and climate. We performed current and natural land cover experiments for January at 56 km grid-spacing, each consisting of an ensemble of four one-month long simulations for both 1850 and 2000. Following Narisma and Pitman [2003], we focus on January where a clear signal to LCC was identified. The boundary conditions for RAMS and our estimates of climate change

**Table 1.** Summary of the Experiments Performed

	LCC	CC	Biospheric CO <sub>2</sub>
<i>NoBio</i>	✓	✓	X
<i>Bio</i>	✓	✓	✓
<i>CC</i>	X	✓	X

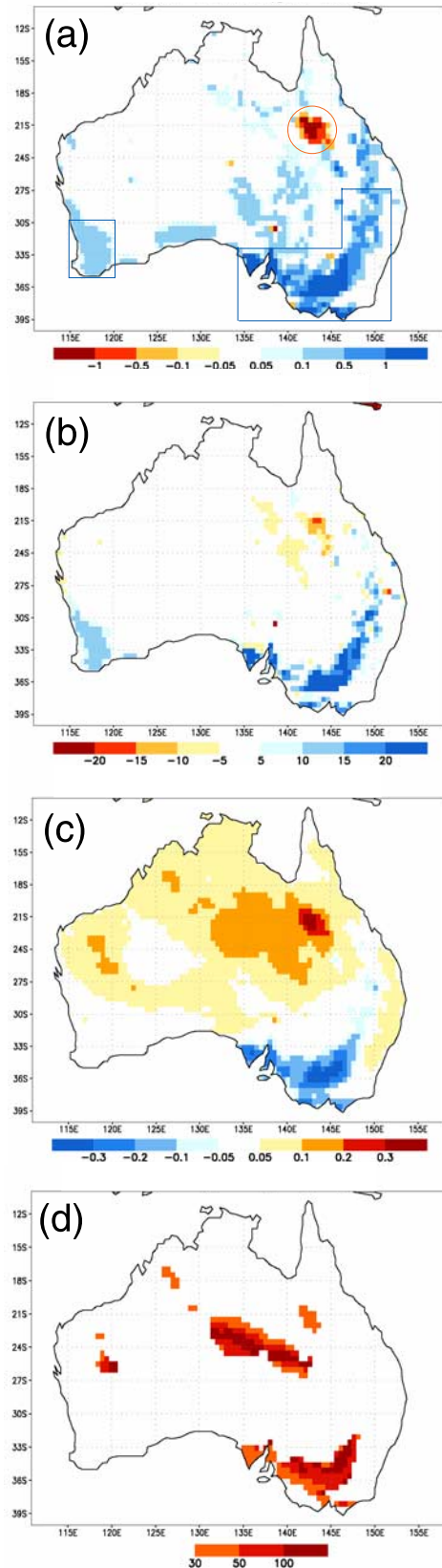
(1850 to 2000) were obtained from four parallel transitory simulations of the CSIRO climate model [Watterson and Dix, 2003].

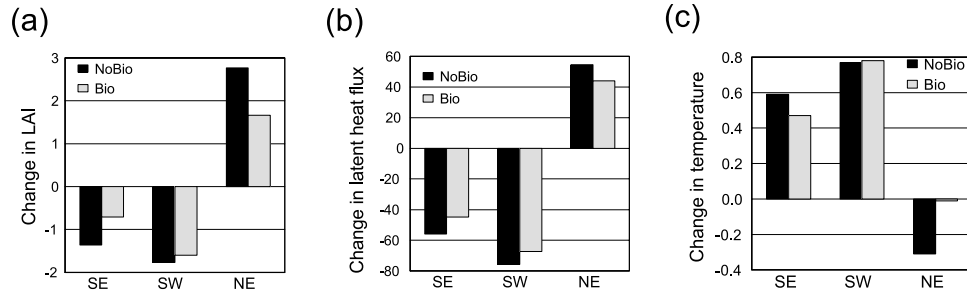
[5] Our first experiment includes LCC (natural changed to current using the same LCC as Narisma and Pitman [2003]), the simulated climate change from 1850 to 2000, and atmospheric CO<sub>2</sub> change (289–369 ppmv). We exclude any biospheric feedback by keeping the CO<sub>2</sub> levels provided to GEMTM at 1850 values but allowing the atmospheric CO<sub>2</sub> to change and affect the radiative fluxes. This experiment (*NoBio*) therefore explores LCC without biospheric feedbacks and parallels Narisma and Pitman [2003]. In the second experiment (*Bio*), changes in land cover, climate change and CO<sub>2</sub> are included and GEMTM is exposed to the changing atmospheric CO<sub>2</sub>, enabling a biospheric feedback. We account for the time-lag between the structural response (weeks or months, see Chen and Coughenour [1994]) and the physiological response (effectively instantaneous, see Chen et al. [1994] for a description) to changes in CO<sub>2</sub> by stabilizing the LAI before each simulation. This is achieved via uncoupled GEMTM simulations forced by seasonal and geographical variations in atmospheric forcing until the annual difference in LAI is  $\leq 0.1$  (i.e., precipitation and temperature feedbacks are not included in this initial LAI estimate). To assess the magnitude of the differences resulting from biospheric feedbacks, we perform a third experiment which isolates the impact of just the simulated climate changes (*CC*). In this experiment, land cover and CO<sub>2</sub> concentrations provided to GEMTM remain at 1850 values and we simulate historical climate change omitting LCC and biospheric feedbacks (Table 1 presents a summary of our experiments). Note that the biospheric feedback does not affect atmospheric CO<sub>2</sub> in our experiments.

### 3. Results

[6] Our results are expressed as  $\Delta\text{LAI}_{\text{Bio}} - \Delta\text{LAI}_{\text{NoBio}}$  where  $\Delta\text{LAI} = \text{LAI}_{2000} - \text{LAI}_{1850}$  (for the example of LAI). It is important to note that the inclusion of the biospheric feedback does not change the sign of the impact of LCC in our simulations, rather this feedback moderates the initial increase or decrease caused by LCC. Figure 1a

**Figure 1.** (opposite) Difference between the impact of LCC simulated with biospheric feedbacks (*Bio*) and without biospheric feedbacks (*NoBio*). (a) LAI difference i.e.,  $(\text{LAI}_{2000} - \text{LAI}_{1850})_{\text{Bio}} - (\text{LAI}_{2000} - \text{LAI}_{1850})_{\text{NoBio}}$ . Regions of human-induced LCC are circled (vegetation change from grass to shrub) or enclosed in polygons (vegetation change from trees to grass); (b) latent heat flux ( $\text{W m}^{-2}$ ); (c) temperature ( $^{\circ}\text{C}$ ); (d) the impact of the biospheric feedback compared to the impact of climate change (experiment *CC*) on temperature.





**Figure 2.** Simulated change (relative to  $CC$ ) in (a) LAI; (b) latent heat flux ( $W m^{-2}$ ); (c) temperature ( $^{\circ}C$ ) for the *NoBio* (black bars) and *Bio* (lightly shaded bars) for Southeast (SE), southwest (SW) and northeast (NE) Australia (see Figure 1).

shows that there is a difference in the  $\Delta LAI$  patterns between *Bio* and *NoBio* (where LAI is prescribed). The change in LAI is smaller (i.e.,  $|\Delta LAI_{Bio}| < |\Delta LAI_{NoBio}|$ ) when biospheric feedbacks are included over areas of human-induced LCC. This is shown in Figure 2a where in all cases the impact of LCC with biospheric feedbacks are smaller than the impacts if biospheric feedbacks are omitted.

[7] In areas where land cover has been converted from trees to grass (boxed in Figure 1a and SE and SW in Figure 2a), LCC reduces LAI but the incorporation of biospheric feedbacks moderates this reduction. Allowing the vegetation to respond to increasing  $CO_2$  enhances grass growth and makes the reduction in LAI following LCC smaller (by about 1.0) than the reduction in *NoBio* (Figure 1a). Biospheric feedbacks also reduce the impact of LCC where vegetation has changed from grass to shrub (circled in Figure 1a, and NE in Figure 2a). In these regions, the increase in LAI following LCC is smaller (but still positive) in *Bio* by about 1.0 indicating that the growth of shrubs in 2000 is relatively slower than the grass leaf growth (i.e.,  $\Delta LAI_{Bio} < \Delta LAI_{NoBio}$ ).

[8] In both cases therefore, biospheric feedbacks moderate the impact of LCC independent of whether LAI is reduced or increased. The vegetation response to increasing  $CO_2$  is not restricted to areas of LCC. In regions where humans have not changed land cover, Figure 1a shows that  $\Delta LAI_{Bio}$  is higher by up to 0.25 than  $\Delta LAI_{NoBio}$ . This is the biospheric feedback enhancing leaf growth: the “fertilization effect”.

[9] The impact of LCC and biospheric feedbacks on  $\lambda E$  is shown in Figure 1b. In both *NoBio* and *Bio*,  $\lambda E$  is decreased in deforested areas and increased in areas of shrub regrowth (Figure 2b). However, our results show that biospheric feedback reduces the magnitude of these impacts of LCC on  $\lambda E$ . Compared to the *NoBio* experiment, the *Bio* experiment simulates a smaller (by about 10–20  $W m^{-2}$ ) decrease in  $\lambda E$  in the deforested regions (SE and SW, Figure 2b) and a smaller increase in  $\lambda E$  in areas of shrub regrowth (NE, Figure 2b). Thus, irrespective of whether LCC causes an increase or a reduction in  $\lambda E$ , biospheric feedbacks tend to moderate this change and hence experiments that do not include this feedback will tend to simulate an excessive impact of LCC on  $\lambda E$ .

[10] Figure 1b also shows some changes in  $\lambda E$  remote from human-induced LCC. This negative change in  $\lambda E$  indicates a smaller increase in  $\lambda E$  in the *Bio* experiments. While LAI has increased in these areas as a result of

biospheric feedbacks,  $\lambda E$  has decreased because the physiological response decreases  $g_s$ . In these areas of non human-induced LCC, the physiological response dominates the structural feedback of increasing LAI.

[11] Changes in  $\lambda E$  may affect rainfall and temperature through the surface water and energy balance. We find no evidence that the biospheric feedback affects precipitation (not shown). The biospheric feedback does affect temperature (Figure 1c). Over south eastern Australia, biospheric feedbacks reduce the warming caused by LCC by 0.1–0.3 $^{\circ}C$  (Figures 1c and 2c) and reduce the cooling over regions of shrub regrowth in Queensland by about 0.2 $^{\circ}C$  (NE in Figure 2c). Thus, the inclusion of biospheric feedbacks reduces the warming caused by LCC in the *NoBio* experiment where grass replaces trees, and reduces the cooling where shrubs replace grass. Over regions where there is no Human-induced LCC, temperature changes of 0.1–0.2 $^{\circ}C$  are widespread. This is the result of the biospheric feedback that lead to large scale warming in *Bio* as the vegetation responds to increasing  $CO_2$  and climate change by reducing  $g_s$  [cf. Sellers *et al.*, 1996].

[12] We test the statistical significance of our results using Wigley and Santer’s [1990] method. We used 1000 permutations of the data and identified those changes that are statistically significant in the point-by-point measures of the mean and variance (NT5 and NF5 in Wigley and Santer, [1990]) at a 95% confidence level. The changes in LAI and temperature over areas of historical LCC are all statistically significant in the point-by-point mean and variance. Further, to the south-west of the region where grass has been replaced by shrubs the simulated change in LAI and temperature are also statistically significant.

[13] To quantify the relative importance of the biospheric feedback on temperature changes, we compared the difference shown in Figure 1c (between *Bio* and *NoBio*) with the changes in temperature due to climate change ( $CC$ ) only. We obtained the percentage difference of the magnitude of biospheric effects relative to  $CC$ : i.e.,  $(|Bio - NoBio|/CC) \times 100$ . Figure 1d shows that the magnitude of the biospheric feedback on temperature in areas of LCC is large in two major regions: in central Australia and in southern Australia. In these regions, the impact of the biospheric feedback exceeds 30% of the  $CC$  impact. While this importance depends on the pattern of climate change simulated by the CSIRO model, this model’s climate sensitivity is comparable to those reported by IPCC [Watterson and Dix, 2003]. To place the biospheric feedback into perspective however, over most of Australia the impact of

simulated climate change is more significant than the impact of the biospheric feedback (although not necessarily the impact of LCC).

#### 4. Discussion and Conclusion

[14] Most modeling experiments that have explored the impact of historical human-induced LCC have only incorporated the direct impact of LCC. These experiments have not incorporated the indirect effect of Human-induced LCC, that is, the impact of climate change and increasing CO<sub>2</sub> on biospheric activity. This biospheric feedback has the potential to increase or moderate the direct impact of Human-induced LCC and to affect the simulation of climate in areas remote from LCC.

[15] Figure 2 summarizes the effect of incorporating biospheric feedbacks in LCC experiments. The biospheric feedback results in negative feedbacks on temperature change. It has decreased the amount of warming (in SE, Figure 2c) and decreased the amount of cooling (NE, Figure 2c) attributed to the impact of LCC in the *NoBio* experiments. These feedbacks on temperature are the consequence of the changes in LAI and  $g_s$  affecting the partitioning of energy between  $\lambda E$  and sensible heat flux and are statistically significant in the point-by-point mean and variance (at a 95% confidence level). We also find the fingerprint of biospheric feedbacks in areas remote from LCC. In these regions, CO<sub>2</sub> enrichment has increased LAI but decreased  $g_s$ . The latter dominated in our experiments and thus decreased  $\lambda E$ . We suspect that the balance between changes in LAI and  $g_s$  will be regionally specific and this is currently under further exploration through simulations that isolate the various mechanisms.

[16] The importance of including biospheric effects is underscored when their magnitude is compared with the CSIRO-simulated changes (experiment *CC*). The changes in temperature in areas of LCC and non LCC resulting from incorporating biospheric feedbacks exceed 30% of that due to climatic change alone (Figure 1d). Hence, we agree with *Betts* [2001] that it is necessary to account for the biospheric feedback when investigating the impact of Human-induced historical LCC. The biospheric feedbacks also seem systematic over Australia so that experiments that omit it will tend to overemphasize the impact of LCC irrespective of whether the LCC is deforestation or recovery.

[17] In summary, the impact of LCC over Australia in January is overemphasized in our simulations unless biospheric feedbacks are included. We stress that our modeling study, focusing on January, cannot be conclusive and that there are ecological aspects of Australian vegetation that may not be captured well by GEMTM. However, our results, using an ensemble of 4-one month simulations for both 1850 and 2000 demonstrate the significance of biospheric feedbacks in historical LCC. Simulations over the 20th Century as part of the Climate of the 20th Century Project (C20C, see <http://grads.iges.org/c20c/>) need to capture these feedbacks in order to represent reasonably the impact of LCC on the changing climate of the 20th Century.

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