The Effect of Including Biospheric Responses to CO₂ on the Impact of Land-Cover Change over Australia

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ABSTRACT: Increasing atmospheric carbon dioxide concentration and the resulting change in temperature affect vegetation physiologically and structurally. These physiological and structural changes are biospheric feedbacks that may enhance or moderate the impacts due to human-induced land-cover change. It is therefore potentially important to include these biospheric feedbacks in experiments that explore the impact of land-cover change on climate. In this paper, it is shown that the vegetation response to higher carbon dioxide concentrations and warmer temperatures moderates the impacts of historical human-induced land-cover change in Australia. The magnitude of these biospheric feedbacks is explored, and it is shown that including them in climate simulations results in smaller land-cover change impacts on latent heat flux (by about 10–20 W m⁻²) and temperature (by about 0.3°C), irrespective of the direction of change caused initially by land-cover change. Further, the magnitude of the feedback on temperature is nonnegligible and can be comparable, at the regional scale, to temperature changes due to increasing atmospheric carbon dioxide concentrations. It is also shown that the biospheric feedback effects are not limited to areas of human-induced land-cover change. Higher simulated temperatures of about 0.05°–0.15°C were found in regions remote from areas of human-induced changes when these biospheric

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feedbacks are included. It is concluded therefore that it is necessary to take biospheric feedbacks into account in climate simulations. Excluding these feedbacks may incorrectly assess the impacts due to land-cover change.

**KEYWORDS:** Biospheric feedback; Regional climate modeling; Land-cover change

### 1. Introduction

Historically, the climate system has been considered to be primarily an atmosphere–ocean problem by global climate and regional climate modelers. In the early 1990s, global climate models included the atmosphere, oceans, sea ice, and a physical representation of the Earth’s surface (Albritton et al., 2001), and experiments using these global models that explored the impact of regional-scale land-cover change simply modified land surface parameter values to reflect a change in the nature of the Earth’s surface (Polcher and Laval, 1994; Lean and Rowntree, 1997; Henderson-Sellers et al., 1993, Gedney and Valdes, 2000; Zhang et al., 2001; Zhao and Pitman, 2002a). Recent developments have led to a redefinition of “climate system” to include the atmosphere, ocean, cryosphere, land surface, and the biosphere (Houghton et al., 2001). The addition of the biosphere is, in part, the consequence of the recent demonstration that the interaction between this component and the rest of the climate system may be profoundly important (Claussen and Gayler, 1997; Texier et al., 1997; Claussen et al., 1998; Cox et al., 2000; Friedlingstein et al., 2001).

Over the last decade, a significant effort has evolved to explore the past, present, and future impacts of human-induced land-cover change (LCC) on climate. Most of these efforts have paralleled the regional-scale experiments noted above, but have perturbed land cover globally according to best estimates (e.g., Klein Goldewijk, 2001; Ramankutty et al., 2002). These studies include the changes in biophysical parameters [albedo, leaf area index (LAI), roughness length, etc.] but do not include any feedback from changes in atmospheric carbon dioxide (CO2) or climate on the structure or function of vegetation (e.g., Chase et al., 1999; Chase et al., 2000; Brovkin et al., 1999; Betts, 2001; Pitman and Zhao, 2000; Zhao and Pitman 2002b; Narisma and Pitman, 2003): in other words, the biospheric feedback (the biospheric or vegetation response via structural or physiological changes to changing CO2 concentrations) is not included.

Increasing atmospheric CO2 and the resulting increase in temperatures and changes in available energy and specific humidity will likely affect vegetation (Betts et al., 1997). These changes in vegetation can be broken down into the physiological effect and the structural response. The physiological and structural responses of vegetation to higher temperatures and CO2 concentration are a decrease in the stomatal conductance ($g_s$) and an increase in the LAI or other biomass, respectively. These effects may lead to contrasting feedbacks on climate, specifically on temperature (Betts et al., 1997; Betts et al., 2000). The decrease in $g_s$ tends to decrease transpiration, affecting the energy partitioning by decreasing evaporation and increasing sensible heat, potentially leading to warming.
Henderson-Sellers et al. (Henderson-Sellers et al., 1995) and Sellers et al. (Sellers et al., 1996) have suggested that this physiological response could enhance the warming due to increasing CO₂ concentrations. Their experiments, however, did not consider changes in LAI that can offset the warming effects of the physiological response as it tends to increase evaporation and hence lower temperatures. Betts et al. (Betts et al., 1997) have shown that the structural feedback of increasing LAI partially offsets the warming due to a decrease in $g_s$, and that the overall impact of these feedbacks on the biosphere is significant particularly at the regional scale. Incorporating the vegetation response to the changes in CO₂ and climate in LCC experiments may therefore either compound or attenuate the LCC impacts simulated from experiments that do not include biospheric feedbacks depending on the balance of structural and physiological feedbacks. Figure 1 illustrates how the contrasting effects of the physiological and structural response can feed back onto the simulated impacts of LCC, which may then affect CO₂.

Following the recognition that the biosphere can moderate or amplify changes in climate forcing, significant efforts have recently been made to explore the impact of LCC on climate including the feedback of changes in climate on land cover. Many experiments have explored the impact of future LCC, commonly but not always expressed in terms of tropical deforestation experiments (Bounoua et al., 1999; Levis et al., 2000; Costa and Foley, 2000; Eastman et al., 2001a; DeFries et al., 2002). These experiments demonstrate a regional- or global-scale impact of LCC on climate that is significant in comparison to the impacts, at a regional scale, of increasing CO₂. Work exploring the impact of LCC on the past (typically on the

![Figure 1. Schematic of how the contrasting effects of the physiological ($g_s$) and structural (LAI) response can feed back onto the simulated impacts of LCC, which may then affect CO₂.](image)
time scale of millennia, e.g., Brovkin et al., 1999; Claussen et al., 2001) has also been performed. Some work exploring the role of LCC on the present climate has also shown amplification of rainfall over urban areas (e.g., Shepherd et al., 2002), reductions in rainfall over natural ecosystems (Lawton et al., 2001), or changes in convective cloud formation (Lyons, 2002; Ray et al., 2003).

To our knowledge, there has been no attempt to explore the significance of the biospheric feedback for assessing the impact of historical LCC on time scales that approximate the Industrial Revolution (the nineteenth and twentieth centuries). Narisma and Pitman (Narisma and Pitman, 2003) showed that historical LCC, without changes in CO₂ or climate and excluding biospheric feedbacks, could affect Australia’s climate significantly, perhaps explaining a significant fraction of observed warming over the twentieth century. Other authors have also shown significant impacts of historical LCC on climate (Copeland et al., 1996; Bonan, 1997; Pielke et al., 1999), but in all these experiments, the biospheric feedbacks were largely omitted. The omission of the biospheric feedback mechanism in modeling historical changes in climate is potentially very significant (Betts, 2001). We know that this biospheric response is important in future land-cover change because it has been shown that future deforestation in the Tropics and subtropics will increase temperatures due to a dominant physiological effect (DeFries et al., 2002). It also seems plausible that the biospheric feedbacks are also important in exploring historical LCC, where CO₂ concentrations have increased by almost 100 ppmv.

In this paper, we examine the role of the biospheric feedback (i.e., its magnitude, sign, and significance) on the climatic impacts due to historical human-induced LCC over Australia. 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 CO₂. We then discuss the implications of including these feedbacks in historical LCC simulations. This paper therefore does not explore the impact of LCC, per se, but rather investigates the feedbacks to identify the effect of including the vegetation response to climate and CO₂ changes on the impact of historical LCC. Note that we do not close the feedback completely because we do not allow atmospheric CO₂ concentration to be modified by the biospheric feedback. Section 2 explains our methodology by describing the modeling and statistical techniques. Section 3 presents our results and discusses the impact and statistical significance of including biospheric feedbacks in historical LCC experiments.

2. Experimental methods
2.1. Modeling methodology

We used GEMRAMS, a model that couples the Colorado State University Regional Atmospheric Modeling System (RAMS; Pielke et al., 1992; Liston and Pielke, 2001) with the General Energy and Mass Transport Model (GEMTM; Chen and Coughenor, 1994; Eastman et al., 2001a). RAMS is a flexible mesoscale meteorological modeling system that offers a variety of options, such as hydrostatic and nonhydrostatic equations, terrain-following coordinates, a variety of cumulus parameterization schemes, explicit microphysics, and radiation options.
Due to its flexibility, RAMS has been applied to many different problems ranging from large eddy simulations (Hadfield et al., 1991) to high-resolution simulations of thunderstorms and convective systems (Pielke et al., 1992). RAMS has also been used to study the effect of vegetation and LCC on weather and climate (Copeland et al., 1996; Pielke et al., 1999; Eastman et al., 2001a; Eastman et al., 2001b; Strack et al., 2003).

RAMS is coupled to GEMTM, a plant model that simulates the dynamic interaction between the biosphere and atmosphere (Chen and Coughenor, 1994). This allows the vegetation to respond to changes in CO$_2$ concentration and climate. At each time step, GEMTM calculates stomatal conductance, separately for C3 and C4 plants, as a function of relative humidity and CO$_2$ concentration (Chen and Coughenor, 1994; Eastman et al., 2001b). The photosynthetic rate is also calculated differently for C3 and C4 plants and is dependent on the atmospheric CO$_2$ and vegetation temperature as well as on the photosynthetically active radiation (PAR) and plant water potential (PWP). The canopy conductance is scaled from the stomatal conductance of shaded and sunlit leaves using the LAI (Chen and Coughenor, 1994), thus the conductance and LAI are coupled in GEMTM. More details on GEMTM and its application and validation at the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) sites can be found in Chen and Coughenor (Chen and Coughenor, 1994). Briefly, we note that Chen and Coughenor (Chen and Coughenor, 1994) showed that GEMTM was able to simulate changes in net CO$_2$ flux, canopy resistance, plant water potential, and canopy and soil-surface temperature realistically. Peel et al. (Peel et al., 2004, hereafter PPHN) have also evaluated RAMS (excluding biospheric feedbacks) and shown that the model simulates the January climate of Australia well.

**2.2. Model configuration**

Using GEMRAMS, we performed simulations on the Australian continent at 56-km grid spacing with 80° latitude grids and 100° longitude grids, 30 vertical atmospheric levels, and 15 soil layers. We used the modified Kuo cumulus parameterization scheme (Tremback, 1990) and the shortwave and longwave radiation scheme described by Chen and Cotton (Chen and Cotton, 1983; Chen and Cotton, 1987).

The model was initialized and driven by boundary conditions taken from a transitory simulation of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mark 2 atmosphere–ocean model (Watterson and Dix, 2003). The CSIRO model has a spatial resolution of approximately 3.2° latitude and 5.6° longitude and includes nine vertical layers for the atmosphere. Climate simulations performed using the B2 (moderate increase) scenarios of the *Special Report on Emission Scenarios* (Nakićenović et al., 2000) and 12-hourly data were used as boundary conditions for GEMRAMS. Twelve-hourly boundary condition updates were found to be acceptable for simulations at grid spacings of around 45 km by Denis et al. (Denis et al., 2003). Our estimates of radiatively forced climate change over Australia were also obtained from the B2 scenario of the CSIRO model.
2.3. Vegetation data

We obtained the land-cover data from the Atlas of Australian Resources on Vegetation by the Australian Surveying and Land Information Group (AUSLIG, 1990). AUSLIG has data for current and natural land cover expressed in floristic types. These floristic types were mapped on to the vegetation classes in GEMRAMS except for eucalypts, which was defined as a separate class. The initial values of the physical characteristics [such as LAI, roughness length ($z_0$), albedo ($\alpha$), vegetation fraction, and root depth] for eucalypts have been thoroughly researched and are Australia specific (PPHN), but other types used default values in GEMRAMS due to the absence of Australian-specific data.

The natural and current land-cover vegetation distributions are shown in Figures 2a and 2b, respectively. Most of the human-induced land-cover change that occurred within the last 200 years occurred in the southeast (SE), southwest (SW), and northeast (NE) parts of the continent. This can be seen in Figure 2c, which shows the difference between the current and natural land cover. Regions in shades of orange to red, which are in the southeast and southwest, are areas where vegetation has changed from trees (usually eucalypts) to grass. The blue areas in the northeast show regions where vegetation cover has changed from grass to woodland, mixed cover, or shrubs (hereafter referred to as “shrubs”). This regeneration of vegetation in the northeast is likely the result of changes in land management practices.

2.4. Soil and LAI initialization

Soil moisture and temperature were initialized using the modeled results from the CSIRO model. We also initialize LAI in those experiments where we allow vegetation to respond to changes in CO$_2$ and climate since the response time of the physiological and structural feedbacks differ. A change in LAI occurs at longer time scales (typically days to months), while the change in $g_s$ is almost immediate. We account for this lag by stabilizing the LAI before each simulation. GEMTM is run offline, that is, uncoupled and without dynamic interaction with RAMS. It is run using forcing data that were previously saved in a coupled January simulation but with seasonal and geographical variations in temperature, rainfall, and radiation imposed on to these data. We stabilize LAI iteratively by running the offline GEMTM for a year and computing for the difference between the initial and final LAI values. We start with an initial LAI value that is 0.25 smaller than the prescribed value (i.e., $\text{LAI}_{\text{initial}} = \text{LAI}_{\text{prescribed}} - 0.25$) to account for the possibility that the stable LAI may be less than the prescribed value. We iterate the offline GEMTM, increasing the LAI by 0.25 at the end of each annual cycle. The LAI for a particular grid point is considered stable when the difference between the initial value and the value after one year of offline simulation is less than or equal to 0.1 (see Figure 3).

2.5. Experiments

Using GEMRAMS, we performed three sets of experiments for January using current and natural land cover. We focus on January because there was a clear
Figure 2. (a) Natural and (b) current vegetation cover for Australia as mapped to the vegetation classes used in GEMRAMS and (c) the difference between natural and current land cover. In (c), areas in shades of orange-red are deforested regions while those in blue are areas of shrub regrowth.
signal on the impacts of LCC previously identified for this particular month (Narisma and Pitman, 2003). Each experiment consists of an ensemble of four monthlong simulations using four parallel transitory simulations of the CSIRO model, and the output is saved every 4 h. The three January experiments are designed to isolate and quantify the relative magnitude of the effect of biospheric feedbacks on the impacts of LCC.

The simulations in the first experiment include LCC together with radiatively forced climate change, but they do not include the vegetation response to increase CO₂ concentrations. We omit the biospheric feedback (the vegetation response to CO₂ change) by keeping the biospheric CO₂ (i.e., the CO₂ concentration felt by the plants) at pre–Industrial Era values (289 ppm) while still allowing the atmospheric

Figure 3. Schematic of the LAI stabilization process used to account for the lag between the structural and physiological response to increases in CO₂ and changes in climate. The offline GEMTM is run iteratively through full annual cycles and LAI is increased by 0.25 at the end of each year until equilibrium is achieved.
CO₂ to change. Hence, this experiment explores straightforward LCC impacts in a radiatively forced changing climate but without including biospheric feedbacks. We term this as the NoBio experiment.

In the second experiment, which we term as the Bio experiment, the simulations include changes in land cover and climate, and the vegetation responds to the increasing CO₂ concentrations. In this case, the CO₂ concentration felt by the plants is the same with the atmospheric concentration, which increases from 289 to the current concentration of 369 ppm. This change in CO₂ leads to a biospheric feedback via a structural and physiological response of the vegetation. We note that changes in the terrestrial carbon balance do not affect atmospheric CO₂ in our experiments (i.e., the full biospheric feedback is not represented).

These first two experiments investigate the difference between simulating the climatic impacts of LCC with and without biospheric feedbacks. To quantify the relative magnitude of this difference and to evaluate the importance of including the biospheric feedback, we perform a third experiment that isolates the effects due to radiatively forced climate change alone, termed as experiment CC. In this experiment, land cover and biospheric CO₂ concentration are kept at 289 ppm. We therefore simulate purely historical climate change and we omit LCC and biospheric feedbacks. This experiment provides a benchmark for quantifying the relative magnitude of the biospheric feedback.

Table 1 summarizes the three experiments. Table 2 shows area averages (for the three major regions of human-induced LCC shown in Figure 2c) for key biophysical variables of vegetation [LAI, albedo (z), and roughness length (z₀)] for experiments Bio and NoBio. Note that Table 2 already shows differences in the parameter values between the Bio and NoBio experiments, specially in LAI and albedo, as a result of the inclusion of the biospheric feedback.

### 2.6. Statistical significance

We assess the statistical significance of the magnitude of the biospheric feedback using the methodology developed by Wigley and Santer (Wigley and Santer, 1990). Using 1000 permutations, we test for statistical significance at a 95% confidence level for the following: the gridpoint-by-gridpoint difference in time means (NT5); the grand mean (T1), which is the overall averaged value computed over space and time; the gridpoint-by-gridpoint difference in temporal variance (NF5); the overall difference in temporal variance (SPRET); and the overall difference in spatial variance (SPREX). We use the p values (observed significance levels) as a measure to evaluate statistical significance. We apply these tests on areas where there is a simulated impact of the biospheric feedback. These areas
include both areas of land-cover change and areas remote from human-induced changes. The impact is statistically significant at the 95% confidence level if \( p \leq 0.95 \) or \( p \leq 0.05 \).

### 3. Results and discussion

The change in CO\(_2\) concentration and the corresponding changes in climate affect both vegetation and local climate. The biospheric feedback effects of changing LAI and \( g_s \) will affect net primary productivity (NPP). These biophysical changes will also have an impact on the partitioning of energy between latent heat and sensible heat flux and hence may modify the simulated changes in temperature and rainfall from experiments that do not include these feedbacks.

We investigate the magnitude of biospheric feedback by first looking at each of the simulated changes in the NoBio and Bio experiments. We then take the difference between these two results; that is, we evaluate \( \Delta \text{LAI}_{\text{Bio}} = \text{LAI}_{\text{currentBio}} - \text{LAI}_{\text{naturalBio}} \) and \( \Delta \text{LAI}_{\text{NoBio}} = \text{LAI}_{\text{currentNoBio}} - \text{LAI}_{\text{naturalNoBio}} \) (for the example of LAI). We note that, excluding \( g_s \), the sign (positive or negative) of the simulated change in the Bio experiment is always the same as the sign of the simulated change in the NoBio experiment. This means that the inclusion of the biospheric effects does not change the sign of most of the impacts of LCC in our simulations, rather it amplifies or moderates these impacts.

#### 3.1. Leaf area index

Figures 4a and 4b show the simulated change (current–natural) in LAI from the NoBio and Bio experiments, respectively. The Bio experiment (Figure 4b) shows a noticeably different LAI pattern compared with the NoBio experiment (Figure 4a). This becomes evident when we take the difference (Figure 4c) between these two patterns [i.e., \( (\text{LAI}_{\text{current}} - \text{LAI}_{\text{natural}})_{\text{Bio}} - (\text{LAI}_{\text{current}} - \text{LAI}_{\text{natural}})_{\text{NoBio}} \)]. Figure 4c shows that the magnitude (i.e., \( |\Delta \text{LAI}_{\text{Bio}}| < |\Delta \text{LAI}_{\text{NoBio}}| \)) of the change in LAI table 2. Change in biophysical vegetation parameters when land cover is changed from trees (natural) to grass (current) in SE and SW, and in NE, where vegetation has changed from trees (natural) to shrub (current).

<table>
<thead>
<tr>
<th></th>
<th>Natural</th>
<th>Current</th>
<th>Current–natural</th>
<th>Natural</th>
<th>Current</th>
<th>Current–natural</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE (deforestation)</td>
<td>4.01</td>
<td>2.64</td>
<td>−1.36</td>
<td>4.05</td>
<td>3.34</td>
<td>−0.71</td>
</tr>
<tr>
<td>SW (deforestation)</td>
<td>4.08</td>
<td>2.31</td>
<td>−1.77</td>
<td>4.08</td>
<td>2.48</td>
<td>−1.60</td>
</tr>
<tr>
<td>NE (shrub regrowth)</td>
<td>2.19</td>
<td>4.96</td>
<td>2.77</td>
<td>3.33</td>
<td>4.99</td>
<td>1.66</td>
</tr>
<tr>
<td>Albedo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SE (deforestation)</td>
<td>0.14</td>
<td>0.17</td>
<td>0.04</td>
<td>0.13</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>SW (deforestation)</td>
<td>0.13</td>
<td>0.17</td>
<td>0.05</td>
<td>0.12</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td>NE (shrub regrowth)</td>
<td>0.19</td>
<td>0.14</td>
<td>−0.05</td>
<td>0.19</td>
<td>0.12</td>
<td>−0.07</td>
</tr>
<tr>
<td>( z_0 )</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SE (deforestation)</td>
<td>1.85</td>
<td>0.61</td>
<td>−1.24</td>
<td>1.85</td>
<td>0.61</td>
<td>−1.24</td>
</tr>
<tr>
<td>SW (deforestation)</td>
<td>1.73</td>
<td>0.28</td>
<td>−1.45</td>
<td>1.73</td>
<td>0.28</td>
<td>−1.45</td>
</tr>
<tr>
<td>NE (shrub regrowth)</td>
<td>0.23</td>
<td>0.84</td>
<td>0.61</td>
<td>0.23</td>
<td>0.84</td>
<td>0.61</td>
</tr>
</tbody>
</table>
over areas of human-induced LCC (Figure 2c) is smaller when biospheric feedbacks are included. Specifically, irrespective of the sign of change, the magnitude of the impact of LCC on LAI with biospheric feedbacks is smaller by about 0.1–1.0 than the impact without biospheric feedbacks.

In these areas of human-induced LCC, the LAI difference between natural and current land cover is affected by the vegetation response to CO2. In regions where land cover has changed from trees to grass, LCC decreases LAI, but the inclusion of biospheric feedbacks moderates this reduction (Figure 4c) as found by Betts et al. (Betts et al., 1997). Higher CO2 concentration in the current land cover has enhanced grass growth and has made the reduction in LAI following LCC smaller than the reduction in the NoBio experiment where the change in LAI is prescribed.

Over areas where vegetation has changed from grass to shrub, the biospheric feedback also reduces the impact of LCC (Figure 4c). Compared with the increase in LAI in the NoBio experiment, the increase in these areas in the Bio experiment is smaller by about 1.0 (Figure 4c). This indicates that the leaf growth of shrubs in current land cover is relatively slower than the grass leaf growth in natural land cover. As a consequence, the difference between the stabilized LAI_{natural} for grass and the LAI_{current} for shrubs in the Bio experiments is less than the difference between the prescribed LAI for grass and shrubs in the NoBio experiments (i.e., |ΔLAI_{Bio(stabilized)}| < |ΔLAI_{NoBio(prescribed)}|).

Overall, therefore, in these areas of human-induced LCC, biospheric feedbacks reduce the impact of LCC independent of the nature of the vegetation change and independent of whether LAI is reduced or increased as a result of LCC. This reduction in the impact on LAI is statistically significant at the 95% confidence level in all of the test statistics (Table 3). The statistical significance of the changes extends from changes in the overall mean, the point-by-point means, time variance, and the spatial patterns, and it is true for all regions of human-induced changes (SE, SW, and NE).

The vegetation response to increasing CO2, however, is not restricted to these areas of prescribed LCC. Figure 4c shows that there is an increase in LAI, of about 0.1–0.5, in the Bio experiment in areas where land cover has not been modified by humans. This is due to enhanced leaf growth under higher CO2. We focus, in particular, on one specific region remote from prescribed LCC southwest of the shrub regrowth area (hereafter referred to as non-LCC; boxed in Figure 4c) where there were simulated changes not only in LAI but also in the other variables analyzed (discussed later). Tests for statistical significance show that the increase in LAI in this non-LCC region is statistically significant for all test statistics in the mean, variance, and spatial and temporal patterns (Table 3). The impact of including biospheric feedbacks on LAI, therefore, is statistically significant not only in regions of human-induced LCC but also in remote areas.

### 3.2. Stomatal resistance

A change in land cover from trees to grass (in SE and SW) increases the stomatal resistance ($r_s = g_s^{-1}$) with or without biospheric feedbacks included (Figures 5a and 5b). In grass to shrub conversion (in NE), however, the signs of the change in $r_s$ for the Bio and NoBio experiments differ. Figure 5a shows that the NoBio experiment has a decrease in $r_s$ but the Bio experiment (Figure 5b) has the opposite
Figure 4. Impact of LCC on LAI (a) without biospheric feedbacks (NoBio), (b) with biospheric feedbacks (Bio), and (c) the difference between the Bio and NoBio experiments. Enclosed areas in dashed gray lines are the approximate regions of land-cover change.
Table 3. Test statistics for the magnitude of the impact of biospheric feedback in deforested regions in SE and SW, areas of shrub regrowth in NE, and in one region remote from human-induced LCC (non-LCC). Numbers in bold are statistically significant values at the 95% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>SE</th>
<th>SW</th>
<th>NE</th>
<th>Non-LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT5</td>
<td>0.01</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NF5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SPREX</td>
<td>0.02</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>r_s (s m⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NT5</td>
<td>0</td>
<td>0.01</td>
<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>T1</td>
<td>0.16</td>
<td>0</td>
<td>0.99</td>
<td>0.67</td>
</tr>
<tr>
<td>NF5</td>
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<td>0.02</td>
<td>0.33</td>
<td>0.1</td>
</tr>
<tr>
<td>SPREX</td>
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<td>1</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>SPRET</td>
<td>0.12</td>
<td>0.05</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>λE (W m⁻²)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>NT5</td>
<td>0.05</td>
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<td>1</td>
</tr>
<tr>
<td>T1</td>
<td>0.16</td>
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</tr>
<tr>
<td>NF5</td>
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<td>0.02</td>
<td>0.33</td>
<td>0.1</td>
</tr>
<tr>
<td>SPREX</td>
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Effect, an increase in \( r_s \). In shrub regrowth areas, therefore, the inclusion of biospheric feedbacks changes the sign of the impact of LCC, resulting in an increase in \( r_s \). This result is consistent with the smaller increase in LAI in these regions and indicates that shrub stomates have partially closed in response to the warmer temperatures and higher CO₂ concentrations. This has increased \( r_s \) and, as a result, slowed down the leaf growth of shrubs and reduced the increase in LAI.

The difference in \( r_s \) between the Bio and NoBio experiments (\( \Delta r_s^{\text{Bio}} - \Delta r_s^{\text{NoBio}} \)) shows that biospheric feedback in deforested areas in SE and SW has moderated the increase in \( r_s \) caused by LCC (Figure 5c). That is, the increase in \( r_s \) in the Bio experiment is less than the increase in the NoBio experiment (\( |\Delta r_s^{\text{Bio}}| < |\Delta r_s^{\text{NoBio}}| \)). Again, this is consistent with the simulated decrease in the reduction in LAI in these regions (Figure 4c). In areas of shrub regrowth, biospheric feedbacks moderate the decrease in \( r_s \) and, furthermore, it also changes its sign (Figures 5a–5c). Hence, our simulations show that the impact of LCC in grass to shrub areas is
Figure 5. Impact of LCC on stomatal resistance, $r_s$ (s m$^{-1}$) (a) without biospheric feedbacks (NoBio), (b) with biospheric feedbacks (Bio), and (c) the difference between the Bio and NoBio experiments. Enclosed areas in dashed gray lines are the approximate regions of LCC.
an increase in $r_s$, instead of a decrease, if biospheric feedbacks are included. These effects of the biospheric feedback in areas of deforestation and shrub regrowth are statistically significant in most tests, for the mean (NT5 and T1) and variance (NF5, SPREX, and SPRET), in all areas of human-induced changes except for the deforested region in SW, which is not significant in NF5 and SPRET (Table 3).

Southwest of the shrub regrowth areas (non-LCC; boxed in Figures 5a and 5b) there is a decrease in $r_s$ for both Bio and NoBio experiments. The difference between the change in $r_s$ in this area shows that the decrease in $r_s$ is reduced (by about 1–10 s m$^{-1}$; see boxed area in Figure 5c) when biospheric feedbacks are included and hence, $r_{s\text{Bio}} > r_{s\text{NoBio}}$. Similar to the shrub regrowth areas, vegetation has closed its stomates because of higher temperatures and higher CO$_2$ leading to a higher $r_s$. This reduction in the decrease in $r_s$, when including biospheric feedbacks, is statistically significant in all tests for variance (NF5, SPRET, and SPREX) but is not significant in the means (Table 3).

3.3. Latent heat flux, $\lambda E$

The decrease in LAI and $g_s$ in trees to grass areas affects the capacity of the vegetation to access soil water and maintain transpiration. As a result, there is a reduction in $\lambda E$ in the deforested regions in both Bio and NoBio experiments (Figures 6a and 6b). In contrast, the increase in LAI in a grass to shrub vegetation change has increased accessibility to water, thereby increasing $\lambda E$. In these areas of shrub regrowth, there is an increase in $\lambda E$ in both experiments.

There is a difference in the magnitude of the changes in $\lambda E$ between the two experiments (Figure 6c). Compared with the NoBio experiment, the Bio experiment simulates less reduction in $\lambda E$, by about 10–20 W m$^{-2}$, in the deforested regions and less increase in $\lambda E$ (by about 10–20 W m$^{-2}$) in areas of shrub regrowth. Thus, in areas of LCC, there are overall smaller changes in $\lambda E$ when biospheric feedbacks are included irrespective of the nature of the change (i.e., whether it is an increase or decrease in $\lambda E$). These smaller changes correlate well with the modeled changes in LAI, where the magnitude of the changes in the Bio experiment is also smaller than those of the NoBio experiment. Further, Table 3 shows that this moderating effect of the biospheric feedback on the impact of LCC on $\lambda E$ is statistically significant at the 95% confidence level in the point-by-point mean (NT5) in all regions of human-induced LCC. For the deforested region in SE, it is not significant in all other test statistics, but it is significant in all tests in SW, and in T1 and SPREX in NE.

There are also changes in $\lambda E$ in regions to the west of the shrub regrowth area where LCC has not been prescribed, and these changes are significant in NT5 and in the two variance tests SPREX and SPRET (Table 3). In this area, both the NoBio and Bio experiments show an increase in $\lambda E$ in 2000, due principally to the influence of the forcing data (boxed area in Figures 6a and 6b). The increase in the Bio experiment, however, is lower by about 2.5 W m$^{-2}$ compared with the increase in NoBio (Figure 6c). Note that Figure 4c shows an increase in LAI in this area in the Bio experiment as a result of CO$_2$ fertilization, but Figure 5c shows a reduction in the decrease in $r_s$ in this same area. Hence, in spite of the increase in LAI in these areas, the physiological response of the vegetation to warmer temperatures has
Figure 6. Impact of LCC on $\lambda E$ (W m$^{-2}$) (a) without biospheric feedbacks (NoBio), (b) with biospheric feedbacks (Bio), and (c) the difference between the Bio and NoBio experiments. Enclosed areas in dashed gray lines are the approximate regions of LCC.
hindered the decrease in $r_s$, and has decreased $g_s$ and consequently decreased $\lambda E$. Thus, in these areas where LCC has not been prescribed, the physiological response dominates the structural effect of increasing LAI.

### 3.4. Net primary productivity

The changes in LAI and $g_s$, resulting from the inclusion of biospheric feedbacks, have also affected NPP. Figures 7a and 7b show NPP for the NoBio and Bio experiments, respectively. There is an increase in NPP in deforested areas and a decrease in regions of shrub regrowth for both experiments. The difference between Bio and NoBio (Figure 7c) shows that the increase in NPP in deforested areas is higher (by about 0.6 in SW and 1.2–1.8 g C m$^{-2}$ yr$^{-1}$ in SE) when biospheric feedbacks are included. Further, Figure 7c also shows that the magnitude of the difference in the decrease in NPP in grass to shrub areas for both cases, with and without biospheric feedback, is less than 0.3 g C m$^{-2}$ yr$^{-1}$. These results for NPP correlate well with the results for LAI and $r_s$. In the deforested regions, there was a reduction in the increase in $r_s$ and there was less decrease in LAI. These moderated impacts on $r_s$ and LAI have led to a higher increase in NPP.

On shrub regrowth areas, including biospheric feedbacks have not affected NPP substantially, and this may be due to the contrasting physiological and structural response to higher CO$_2$ and warmer temperature, where the increase in LAI is counteracted by the increase in $r_s$.

Results from the Bio experiment also show a marked difference in areas remote from LCC (Figure 7c). In these areas where LCC has not been prescribed, there is a simulated general increase (about 0.3–0.6 g C m$^{-2}$ yr$^{-1}$) in NPP in most of the continent as a consequence of the vegetation responding to higher CO$_2$.

### 3.5. Rainfall and temperature

The changes in $\lambda E$ affect the water balance and the repartitioning of available energy and may, therefore, affect rainfall and temperature. Figures 8a and 8b show the change in rainfall patterns ($P_{\text{current}} / P_{\text{natural}}$) for the Bio and NoBio experiments. The difference pattern between these rainfall changes (Figure 8c) appears to be random. We note, however, that in some deforested regions in SE (boxed area in Figure 8c), the change in rainfall magnitude in the Bio experiment is smaller by about 0.1 mm day$^{-1}$ than the change in NoBio. These are areas where rainfall has increased (boxed area in Figures 8a and 8b), and the inclusion of biospheric feedbacks appears to have reduced this increase in rainfall. Except for T1, this reduction in rainfall is statistically significant in all test statistics in the means and variance performed (Table 3).

In terms of temperature, the decrease in $\lambda E$ in deforested regions has increased surface temperature in both Bio and NoBio experiments (Figures 9a and 9b). This warming, however, is greater when biospheric feedbacks are not included, and this is evident when we take the difference of the changes in temperature between the two experiments ($\Delta T_{\text{Bio}} - \Delta T_{\text{NoBio}}$) (Figure 9c). The NoBio experiment simulates the warming impact of LCC in deforested areas by as much as 0.3°C more than the Bio. This smaller increase in temperature in the Bio experiment is a result of the smaller decrease in $\lambda E$ in these regions (Figure 6c). Including biospheric
Figure 7. Impact of LCC on NPP (g C m$^{-2}$ yr$^{-1}$) (a) without biospheric feedbacks (NoBio), (b) with biospheric feedbacks (Bio), and (c) the difference between the Bio and NoBio experiments. Enclosed areas in dashed gray lines are the approximate regions of LCC.
Figure 8. Impact of LCC on rainfall (mm day$^{-1}$) (a) without biospheric feedbacks (NoBio), (b) with biospheric feedbacks (Bio), and (c) the difference between the Bio and NoBio experiments. Enclosed areas in dashed gray lines are the approximate regions of land-cover change.
Figure 9. Impact of LCC on rainfall temperature (°C) (a) without biospheric feedbacks (NoBio), (b) with biospheric feedbacks (Bio), and (c) the difference between the Bio and NoBio experiments. Enclosed areas in dashed gray lines are the approximate regions of LCC.
feedbacks, therefore, has moderated the increase in temperatures caused by LCC, and this moderating effect is statistically significant in NT5 and NF5 (Table 3).

In areas of shrub regrowth, both Bio and NoBio simulated an increase in temperature due to the strong influence of the forcing data, which exhibits a strong climate change signal of warming temperatures in the northern part of Australia (Figure 10). Although this is not evident in Figures 9a and 9b, the change in vegetation cover from grass to shrub reduces this increase in temperature relative to climate change, and thus there is cooling in these areas of shrub regrowth. The magnitude of the cooling, however, is decreased by up to 0.3°C when biospheric feedbacks are included (Figure 9c). This reduction in cooling is statistically significant in NT5 and NF5 (Table 3) and is consistent with the simulated changes in $\lambda E$ where there was a smaller increase $\lambda E$ in the Bio experiment in areas of shrub regrowth (Figure 6c). In these areas, biospheric feedbacks offset the cooling effect of changing the land cover from grass to shrub.

Higher simulated temperatures were found in the Bio experiment in the region remote from human-induced LCC to the west of the shrub regrowth area. Figure 9c shows that compared to NoBio, the Bio experiments are warmer by about 0.05°C–0.15°C in this non-LCC region. This increase in temperature is statistically significant in NT5 and NF5, and it is a result of the smaller increase in $\lambda E$ (Figure 6c). In these areas, the incorporation of biospheric feedbacks has led to higher temperatures due to the physiological feedback dominating the structural feedback.

### 3.6. Relative importance of biospheric effects on temperature

We quantify the relative importance of the biospheric feedbacks on temperature changes by comparing the difference between the NoBio and Bio experiments’ simulated changes in temperature ($T_{current} - T_{natural}$) (Figure 9c) with the changes in temperature simulated due to radiatively forced climate change alone from the CC experiment (Figure 10). We calculated the percentage difference of the magnitude of biospheric effects relative to climate change \{i.e., 100 \times \text{abs}[(\Delta T_{Bio} - \Delta T_{NoBio})]/CC\}.

Figure 11 shows that the magnitude of the biospheric feedback on temperature in areas of LCC can be comparable to the impact of radiatively forced climate change alone. Specifically, the impact of including biospheric feedbacks is large in central and in southern Australia, where its magnitude is at least 30% of the CC impact. Although the significance of this comparison depends on the climate change pattern simulated by the CSIRO model, we note that the climate model’s climate sensitivity is comparable to those reported by the Intergovernmental Panel on Climate Change (IPCC; Watterson and Dix, 2003).

### 4. Conclusions

We have investigated the effect of including biospheric feedbacks on the impacts of land-cover changes (LCCs). Changes in CO$_2$ concentration and temperature affect vegetation structurally and physiologically and using a regional climate model coupled to a dynamic plant model (GEMRAMS) has allowed us to explore the role of these biospheric feedbacks in LCC experiments. We simulated the
impacts of LCC with and without biospheric feedbacks and in all of the simulated changes, except for the change in $r_s$ in shrub regrowth areas, incorporating biospheric feedbacks has moderated the impact of LCC regardless of the sign of these impacts (Figures 12a–12d). That is, the biospheric feedback acts as an opposing influence on most of the variables reported here. It has decreased the reduction in LAI following human-induced LCC in areas of trees to grass conversion in the SE and SW parts of the continent (Figure 12a). It has also lessened the increase in $r_s$ in these areas (Figure 12b). As a result, the inclusion of biospheric feedbacks has moderated the reduction in $\lambda E$ (Figure 12c) and consequently decreased the amount of warming in these deforested regions (Figure 12d).

In the northeast areas of the continent where grass has been converted into shrub, biospheric feedbacks have moderated the increase in LAI resulting from LCC (Figure 12a). It has also increased $r_s$ and reversed the sign of the LCC impact of decreased $r_s$ in the NoBio experiment (Figure 12b). Incorporating biospheric

Figure 10. Simulated change in climate (experiment CC) from the CSIRO climate model. Enclosed areas in dashed gray lines are the approximate regions of LCC.
feedback has, therefore, moderated the increase in $\lambda E$ (Figure 12c) in these areas of shrub regrowth and has reduced the cooling effect of LCC (Figure 12d). Our results also show that biospheric feedbacks are not limited to areas where LCC has been imposed, and we find structural and physiological effects in areas remote from human-induced LCC. In these regions, CO$_2$ enrichment has increased LAI but has partially closed the stomates and thus increased $r_s$. This physiological response dominated and, as a result, the change in $\lambda E$ is reduced, resulting in an increase in temperature in these areas where LCC has not been prescribed when biospheric feedbacks are included.

The importance of including biospheric effects is underscored when its magnitude is compared with the modeled changes in climate (CC). Results show that the changes in temperature resulting from incorporating both structural and physiological effects in areas of LCC and areas where LCC has not been prescribed are at least 30% of that due to climatic change alone.
Figure 12. Simulated changes relative to CC in SE, SW, and NE in (a) LAI, (b) $r_s$ (s m$^{-1}$), (c) $\lambda E$ (W m$^{-2}$), and (d) temperature (°C). Black bars represent data from the NoBio experiment; lightly shaded bars represent data from the Bio experiment.
Hence, we conclude that it is necessary to take biospheric feedbacks into account when investigating the impacts of LCC over Australia. We note that there are uncertainties involved in the physiological and structural response of the vegetation to changing CO₂ and climate and that the response may depend on the model and the imposed radiatively forced climate change (Kergoat et al., 2002). Our results, however, support Betts’ (Betts, 2001) conclusion that it is necessary to include these feedbacks when investigating the impacts of historical LCC, and we have also shown that the effects of including these feedbacks are nonnegligible and statistically significant. Experiments over Australia that do not include these feedbacks may therefore overemphasize the simulated impacts of LCC. This is particularly a concern in experiments that may add LCC over the nineteenth or twentieth centuries for detection and attribution studies. Unless biospheric feedbacks are included with these LCCs, the prescribed changes in land cover are likely to lead to an overestimation of the climate impact of historical LCCs over Australia. Further experiments are required before we can extrapolate this conclusion to other regions.

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