Impact of Land Cover Change on Climate and El Niño in Australia

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EXTENDED ABSTRACT

Climate impacts of land cover change (LCC) are still a subject of discussion despite growing evidence that LCC affects global and regional climates (Zhao et al. 2001; Timbal and Arblaster 2006; Pielke et al. 2002; Narisma and Pitman 2003). To investigate the climate impacts of LCC, this paper presents results for two sets of 10 member ensemble experiments using CSIRO atmospheric GCM.

The CSIRO climate model is a fully coupled atmosphere, land surface, sea ice and ocean model, with a model horizontal resolution of ~1.8^{o} grid increment and 18 vertical levels. In this study, we used the uncoupled version where ocean and sea ice components were represented by observed seasonally varying sea surface temperatures and sea ice data. We quantified changes in land surface parameters and impacts on mean climate from the pre-European (1788) to modern day (1990) land covers and impact of ENSO on the strength of surface temperature anomalies during second half of 20th century. Pre-clearing land surface parameters were generated by extrapolating modern-day values of remnant native vegetation to the pre-European extents of each land cover class. The extrapolation was performed for Australian continent at 8 km spatial resolution and the fine scale parameters then aggregated using Shuttleworth's (1991) approach to coarse resolution aggregated for model.

The largest differences between pre-European and modern day surface parameters were in eastern Queensland, southwest Western Australia, and New South Wales/Victoria. In eastern Queensland, vegetation fraction and leaf area index during the summer decreased by 14% and 20% respectively. This corresponded to a surface albedo increase of 4%. Stomatal resistance increased by 3% and surface roughness decreased by 54%. In New South Wales/Victoria, similarly large decreases in vegetation fraction (19%) and LAI (23%) caused an albedo increase of 7%, while there was a corresponding 46% reduction in surface roughness. In southwest Western Australia, replacement of native woodlands with predominantly winter grains and crops resulted in a modest decrease in vegetation fraction (5%) and LAI (2%) during winter, while stomatal resistance decreased by 15%. However, surface albedo increased by 14% due to higher reflectance of sandy soils. Overall, the largest impact of land cover change on land surface parameters occurred in eastern Australia.

Our results showed that modification of vegetation in eastern Queensland and New South Wales/Victoria contributed to increases in area-averaged surface temperatures of 0.19°C and 0.63°C in the present-day compared to the pre-European values. In New South Wales/Victoria, area-averaged total rainfall decreased by 2.5%, while in eastern Queensland there was a rainfall decrease of 5.2%. The impact of LCC on the winter climate of southwest Western Australia was a cooling of 0.14°C, even though albedo increased. This coincided with a small increase in winter rainfall by 0.6% and soil moisture by about 12%. Our winter response of increased rainfall is at odds with Pitman et al (2004) and Timbal and Arblaster (2006) although annual average rainfall, showing a decline of 0.24%, is consistent with their results. Nevertheless, even this decline is too small to be attributable to the influence of LCC. Further studies are needed to address the exact cause of this discrepancy.

Composites of summer surface temperatures during the five strongest El Niño and La Niña episodes from 1950-2003 showed significant warming under present-day land cover conditions. However, increases in surface temperatures in eastern Australia were the highest during both episodes. On average, the strongest warming (≈ 3.6ºC) occurred during 1982/1983 El Niño in eastern Australia and southwest Western Australia, the regions of largest land cover change. The surface temperature were similar for 1997/98 and 2002/2003 El Niño years, indicating the land surface forcings act to amplify the effect of El Niño on the surface climate of Australia.

The findings indicate that replacing the native woody vegetation with crops and grazing has resulted in significant changes in regional climates, with a shift to warmer and drier conditions, especially in eastern Australia, the nation's major agricultural production zone.

1.0 INTRODUCTION

Human influence on the earth's natural climate system is unprecedented (Lambin and Geist 2006). There is emerging evidence that vegetation cover change has a radiative impact on regional climate systems (Zhao et al. 2001; Roy and Avissar 2002; Timbal and Arblaster 2006). This impact is manifested through changes in albedo and evaporation and transpiration processes and partitioning of sensible, latent and ground heat fluxes (Pielke et al. 2002).

In Australia, clearing of native woody vegetation began after European settlement, and has continued till today, has been central to the production of agricultural commodities, resulting in over 1.2 million km^2 (~13% of continent) being cleared (Barson et al. 2000, Kirkpatrick 1999). Extensive grazing now covers ~43% of the continent and intensive cropping and improved pastures ~10%, with much of this area affected by degradation to some extent (McKeon et al. 2004). This transformation of the Australian landscape has been paralleled by a decline in mean annual rainfall in over last fifty years in coastal Queensland and New South Wales, and in southwest West Australia since the 1970s (Smith 2004). Pitman et al. (2004) found that clearing vegetation in southwest Western Australia had contributed to the drying effect in that region. Timbal and Arblaster (2006) demonstrated that land clearance can be seen as an additional forcing compounding the changes due to large-scale MSLP changes, thus explaining the possibilities for average annual rainfall decline in southwest Western Australia. However, Nicholls (2006) attributed these changes in rainfall primarily to changes in sea-level surface pressure in the Indian Ocean. McAlpine et al. (2007) showed a consistent and statistically significant summer warming of $2^{\circ}C$ and 5-30% drying over southeastern Australia due to LCC. It is therefore likely, that there is an LCC signature in the climate record of Australia.

Australia's fragile climate system is provoking more challenges for climate research and mitigation of climate change today, than ever. The eight Australian droughts and degradation episodes since 1870 have captured a lot of public attention (Stone et. al. 2003). There is urgency to investigate the causes of the observed rainfall decline and persisting droughts that are affecting a large section of the Australian economy. The recent droughts are a cause for concern (Karoly et al. 2003), for present and future water and food security, primarily because of its detrimental influence on the functioning of Murray-Darling river system, the nations major "food basket". The Murray-Darling basin covers an area of approximately 14% of Australian continent and includes the nation's three longest rivers, accounting for 41% of gross agricultural productions and 70% of irrigation water (Nicholls 2003). Whether the recent trend of persisting droughts is part of natural phenomenon, driven by natural climate variability or driven by anthropogenic climate change, is a question that remains unanswered, although some views favour natural climate variability causes. Nevertheless, climate models project increases in drought frequency and severity in response to greenhouse gas (GHG) forcings (Risbey et. al. 2003). Hence GHG forcings trigger increases in land surface temperatures and higher potential evaporation. Coupled with low rainfall, high surface temperatures lead to moisture deficits, resulting in more severe drought episodes (Risbey et. al. 2003).

The attribution of Australian droughts to periodic warming of the equatorial Pacific Ocean through the El Niño Southern Oscillation (ENSO) phenomenon is well recognized. This is evident from many studies which have demonstrated that El Niño years coincide with low rainfall over eastern Australia (McBride and Nicholls 1983; William et. al. 1986, Cai 2003). While ENSO is a natural phenomenon, it manifests itself differently in response to anthropogenic forcings that amplify and/or dampen strengths of its inter-annual and inter-decadal natural variability (Palmer 1993). It is agreed that changes to natural mode of climate variability are influenced by long-term changes in greenhouse gas forcings. This notion is consistent with increases in frequency of ENSO events in recent decades (IPCC 2007) in Australia, which corresponds closely with increasing severity of droughts.

As indicated by Kininmonth (2003), the 2002/2003 drought is not totally manifested by natural climate variability, but to some extent, attributable to anthropogenic-induced climate change. The emerging links between LCC and its dynamical role on earth-atmosphere interactions and impacts on natural climate variability provides growing evidence to seriously consider the notion that LCC forcing on natural mode of ENSO plays a major role in the evolution, strength and progression of droughts. Thus answers to the question that are presently unclear and needs to be sought are, "*to what extent has land cover change in southeast Australia and* *southwest Western Australia impacted regional climate and exacerbated recent ENSO related droughts in eastern Australia*"?

This paper addresses the above questions by presenting a 10 member ensemble experiment for pre-European and modern day land conditions for the period 1949-2003 using CSIRO's atmospheric GCM. This was achieved by: 1) calculating changes in land surface parameters of leaf area index, vegetation fraction, surface albedo, surface roughness and stomatal resistance from pre-European to modern day land covers, 2) determining regional changes in surface energy and hydrology fluxes and temperatures, and 3) calculating changes in surface temperatures during major El Niño and La Niña since 1950.

2.0 METHODOLOGY

2.1 Description of global and Australian land surface parameters

We used recent global land surface data (Lawrence 2004), which had relatively fine spatial resolution and covered over longer and more representative time periods than were used in generating the land surface parameters of Dorman and Sellers (1989). The mapping of Australian LCC was derived from the structural and floristic vegetation maps of Australian vegetation, captured in 1988 (AUSLIG 1990), and simplified to modern-day and pre-European land cover maps in the land cover classes according to Graetz et al. *(*1995). The available global and Australian data of vegetation characteristics was translated to the vegetation classification based on the SiB approach (Sellers et al. 1996) to be used by the CSIRO atmospheric GCM. Pre-clearing land surface parameters were generated by extrapolating modern-day monthly values of remnant native vegetation to the pre-European extents of each land cover class. The extrapolation was performed for the Australian continent at an 8 km resolution and aggregated using the approach of Shuttleworth (1991).

2.2 Description of climate model and experimental design

We used the CSIRO Mark 3 atmospheric GCM to model the impact of LCC on regional climate and ENSO in Australia. The CSIRO model, described in Gordon et al. (2002), is a fully coupled, process based, atmospheric, land surface, sea ice and ocean model with a T63 horizontal resolution of ~ 200 km and 18 vertical levels designed to simulate the global climate. In this study, we used the uncoupled version where ocean and sea ice components were represented by observed seasonally varying sea surface temperatures and sea ice data (Rayner et al., 1996). The model inputs historical sea surface temperatures and sea ice, which is different from traditional approaches that use long term average seasonal values of surface temperatures and sea ice (Rayner et al. 1996). We followed the design of Climate of the 20th Century project (Folland et al. 2002) which allows direct comparisons between the observed and modeled data even for individual ENSO events, which are known to strongly influence the Australian climate (Schubert et al. 2004).

To evaluate impacts of historical vegetation cover change on characteristics of land surface and spatial climate, we completed two sets of 10 model ensemble experiments for the period 1949-2003, one for pre-European vegetation cover characteristics and one for modern day vegetation cover characteristics. Global vegetation characteristics aside from Australia were set at modern day conditions. The only difference between the experiments was the surface parameters, which were representative of the modern day and pre-European conditions.

3.0 RESULTS

3.1 Aggregated Changes in Land Surface Parameters in Major Regions of Land Cover Change

To illustrate interactions between land surface characteristics and spatial climate at regional-scales, we selected three regions in Australia with largest concentration of land cover change (Fig. 1). To assess impacts of LCC on annual and seasonal climates, we spatially averaged surface parameters and selected climate variables across the respective model grid points (Fig. 1).

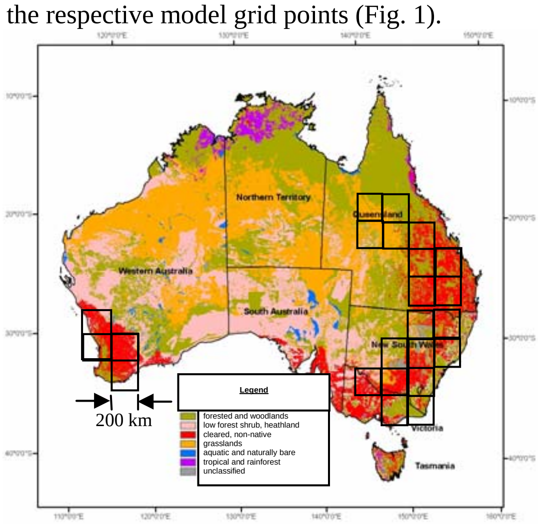

Figure 1: Current land cover map of Australia showing major cleared and forested areas. Note the red areas are cleared regions and/or modified vegetation. The boxes represent the model grid.

On the seasonal basis and spatial scale, the largest climatic impact was during the summer in eastern

New South Wales/Victoria and eastern Queensland and southwest Western Australia which has a winter dominant rainfall regime (Smith 2004). These are detailed in Table A1.

In Queensland, native vegetation clearing caused a vegetation fraction decrease of 14%, the greatest being in coastal regions where native vegetation cover was the densest and decreased in semi-arid inland where the native vegetation cover was more open. The reduced vegetation fraction resulted in an increase of 4% in surface albedo. This was due to the change in optical properties of the land cover (Peixoto and Oort 1992). The leaf area index (LAI) changes were consistent with fractional vegetation changes, showing a decrease of 20%. Stomatal resistance showed a small increase of 3% due to a change from native trees to mostly exotic grasses. Replacement of native forests and woodlands with seasonal crops and improved pastures has also resulted in a reduction in surface roughness of 54%. Land cover change in eastern New South Wales and Victoria has led to a larger decrease in vegetation fraction (19%) and leaf area index (23%) during summer, a reduction of 46% in surface roughness and a 7% increase in surface albedo. There was a significantly large reduction in vegetation fraction (19%) and leaf area index (23%). The stomatal resistance changes were quite small (0.2%). The replacement of native woodlands, shrub lands and grasslands in southwest Western Australia with predominantly winter grains crops has resulted in a more modest decrease in fractional vegetation cover of 5%. This modest reduction is also reflected by a decrease in LAI of 12%. However, albedo showed an increase of 14% due the higher reflectance of the underlying sandy soils. The stomatal resistance decreased by 15% and surface roughness increased by 35%.

Southeast Queensland - DJF

Surface Parameters	Pre European	modern day	% diff
Surface albedo	0.17	0.17	4
Leaf area index	1.12	0.90	-20
Vegetation fraction	0.33	0.28	-14
Stomatal Resistance	103.3	105.9	3
Surface Roughness	0.50	0.23	-54

Eastern New South Wales/Victoria - DJF

Surface albedo	0.16	0.18	7
Leaf area index	2.92	2.26	-23
Vegetation fraction	0.61	0.49	-19
Stomatal Resistance	96.9	96.7	-0.2
Surface Roughness	0.72	0.39	-46

Southwest Western Australia - JJA

Surface albedo	0.17	0.19	14
Leaf area index	1.03	0.91	-12
Vegetation fraction	0.38	0.36	-5
Stomatal Resistance	98.1	82.9	-15
Surface Roughness	0.29	0.19	-35

Table 1: Aggregated area-averaged (%) changes in land surface parameters obtained from CSIRO atmospheric GCM, in three major Australian regions of land cover change during summer (DJF) and winter (JJA). Data averaged over nine model grid points for eastern Queensland, four for southwest Western Australia and ten for eastern New South Wales.

3.2 Area-Averaged Regional Impacts on Seasonal Climates in Three Major Regions of LCC

In Queensland, the modification of native vegetation with mostly cropping and improved pastures has resulted in a warmer climate, where the mean surface temperature increased by 0.19ºC during the summer (Table A2). This increase corresponded to the significant increase in surface albedo. Reduced vegetation fraction contributed to a decrease in both surface evapotranspiration and latent heat flux by 3.5%, while sensible heat flux increased by 3.2%. The reduced surface roughness resulted in an increased near-surface wind of 7%. Our results also showed marked changes in surface hydrology in Queensland. The area-averaged rainfall decreased by 2.5%, and top soil moisture reduced by 1.7% while bottom soil moisture increased by 19.4%.

In eastern New South Wales/Victoria, summer surface temperature warming was larger than for the other two regions, with a rise in mean surface temperature of 0.63ºC (Table A2). This was consistent with a larger absorption of surface energy of ~ 5.2%, as opposed to only 2% increase for eastern Queensland. A larger decrease in latent heat flux of 7.3% and increase in sensible heat flux of 1.5% occurred in New South Wales/Victoria, producing a significant change in the Bowen ratio which can be expected to offset the energy transfer rates in the atmosphere through evaporative and convective moisture fluxes. A marked reduction in LAI and vegetation fraction has led to a large decrease in evapotranspiration rates of 6.8% which was consistent with a decrease in latent heat fluxes of 1.5%. The reduced surface roughness resulted in an increase in wind speeds of about 9.2%.

Overall, the New South Wales/Victoria region experienced a largest rainfall deficiency of 5.2% when compared with other regions of land cover change. The changes in surface hydrology also included a decrease in top soil moisture by 4% and bottom soil moisture by 14.9%, together with an increase in surface run-off by 10%.

The patterns of climate change produced by land cover change during the winter of southwest Western Australia was distinctly different from the summer patterns for eastern

	MAJOR LAND COVER CHANGE REGIONS IN AUSTRALIA								
	Southeast Queensland			**Eastern New South Wales/Victoria**			**Southwest Western Australia**		
	Annual	**DJF**	**JJA**	**Annual**	**DJF**	**JJA**	**Annual**	**DJF**	**JJA**
Latent heat flux (±0.1%)	-2.5	-3.5	0.6	-4.0	-7.3	-2.6	-0.6	-7.8	1.1
Sensible heat flux (±0.2%)	0.8	3.2	-1.4	-0.5	1.5	-2.2	-5.7	-4.4	-12.1
Net surface energy (±0.1%)	-0.2	2.0	-1.8	2.0	5.2	0.0	1.0	1.2	-2.0
Mean surface temperature (ºC, ±1%)	0.03	0.19	-0.10	0.21	0.63	0.04	-0.06	0.18	-0.14
Mean surface wind speed (±2%)	6.5	7.0	6.7	7.9	9.2	8.8	3.6	4.3	3.7
Total rainfall (±0.1%)	-1.40	-2.50	-0.78	-2.70	-5.20	-0.70	-0.24	-0.88	0.60
Surface run-off (±5%)	7.7	5.7	20	13.1	10	24	149	931	161
Top 10 cm soil moisture (±2%)	1.1	-1.0	6.1	3.9	-4.0	7.6	10.5	4.5	12.1
Bottom soil moisture (±1%)	3.1	1.7	4.1	11.0	14.9	8.4	14.9	22.0	11.6
Evapotranspiration (±0.5%)	-2.2	-3.5	0.6	-3.8	-6.8	-2.6	-0.56	-7.8	1.1

Table 2: The area averaged % changes in surface parameters and underlying Australian regional climates, from 10-member ensemble CSIRO GCM experiments. Note: surface temperature change shown in ºC.

regions. The temperature response in winter was opposite to summer response for eastern Queensland and eastern New South Wales. This resulted in a slight cooling effect, with surface temperature decrease of ≈ 0.14ºC. The changes in near surface wind speeds were consistent with proportionally smaller decrease in surface roughness in southwest Western Australia and resulted in a modest wind speed increase of 3.7%.

A small increase in evaporation rates (~ 0.03%) caused a modest increase in latent heat flux of 1.1% and a large decrease in sensible heat flux (12.1%). The winter season experienced a small increase in rainfall of 0.6% although previous investigations (e.g. Timbal and Arblaster 2006; Nicholls 2006; Pitman et al. 2004) had found significant rainfall declines in southwest Western Australia. Our results also showed that average annual rainfall in southwest Western Australia has declined by 0.24% which is again too small to be attributable to the influence of LCC. Our experiments show that deforestation has had little impact on the rainfall of southwest WA, which again contradicts the results of Timbal and Arblaster (2006) and Pitman et al. (2004). The reason for this discrepancy is currently unclear and warrants further investigation and another independent study.

3.3 Mean Cumulative Impact of Land Cover Change on ENSO Episodes from 1950-2003

The 2002/2003 El Nino event had pronounced impact on south-eastern Australia, resulting in large reduction of primary production caused by severe and extensive drought conditions and significant stress on the national economy (Cai 2003).

To assess the influence LCC on warming trends in Australia during different phases of ENSO, we compared surface temperature patterns during eight strongest El Niño and La Niña episodes since 1950. Figures 2 (a, b) compare the differences in surface temperatures between pre-European and modern day land covers using composite of five strongest La Niña and five strongest El Niño episodes over 50 years. Results predicted a warming of almost up to 2ºC over the entire continent during the La Niña episode. This warming was the strongest in regions of significant LCC. During warm episode, similar warming occurred but was only confined to regions of southwest WA, south-eastern coastal regions and in a band stretching from middle Australia and northern half of the continent. The areas of greatest warming (≈0.8 to 2ºC) coincided with the three regions of greatest LCC.

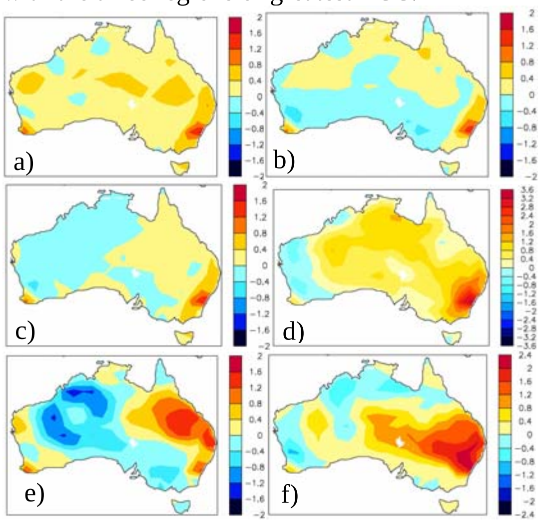

Figure 2: Simulated surface temperature difference (1951-2003) between present-day and pre-European land covers for: a) DJF composite of five strongest La Niña (1955/56, 1973/74, 1975/76, 1988/89 and 1998/99); b) DJF composite of five strongest El Niño (1957/58, 1972/73, 1982/83, 1991/92 and 1997/98); c) long term DJF average; d) 1982/83 DJF El Niño; e) 1997/98 DJF El Niño, and f) 2002/2003 El Niño.

The long-term anomaly of surface temperature during DJF (Fig. 2c) showed a warming of up to 2ºC in eastern Australia, in inland Queensland and southwest Western Australia. However, warming signal was pronounced over eastern Australia and southwest Western Australia where surface temperature rise was between 1.2 to 2ºC. The composites and long term averages show that LCC leads to increases in surface temperature, not only in regions of LCC, but also in other areas to a lesser magnitude.

Since it appears from Fig. 2b that the temperature response during El Niño is distinctly different from that of the La Niña episode, we examined the temperature signals during three strongest El Niño years more closely (i.e. 1982/83, 1997/98 and 2002/2003). It was evident that land cover perturbations have triggered the 1982/83 El Niño to produce marked warming between 0.4 - 3.6ºC in almost ¾ of the continent. Amongst the three regions of major LCC, the greatest increase was in eastern New South Wales and a section of Queensland where the mean surface temperature rose by almost 3.6ºC.

Our results also showed that the impact of land cover change was not so severe during the 1997/1998 El Niño (Fig. 2e) compared to the impact during the 1982/1983 El Niño (Fig. 2d) which severely affected almost the whole of Australia. However, increased temperatures in inland Queensland, eastern Queensland, eastern New South Wales and southwest Western Australia were quite prominent during both the 1997/98 El Niño years.

Comparisons of the modelled results for modern day and pre-European land cover characteristics for the 2002/2003 El Niño showed that for the modern day conditions, surface temperature was warmer by 0.75-2°C in a band stretching from eastern Australia to Central Australia (Fig. 2f). Although the pattern of response was similar to that of 1997/98 El Niño, the magnitude of temperature increase was higher by 0.4ºC in eastern Australia. For comparison of modeled results with observations, we refer to the work of Cai et al. (2003), which has described the simulations of ENSO using CSIRO’s Mark 3 atmospheric GCM. Using model outputs, they showed that major ENSO indices, periodicity and spatial patterns of the modeled ENSO compare well to those observed over last 100 yrs. This good simulation is achieved despite some deficiencies in model climatology, in particular the climatological tropical Pacific sea surface temperatures. The comparisons between modeled and observed equatorial thermocline structure reveal that the model thermocline depth (depth of 20°C isotherm) is shallower, whereas the spread or thickness of modeled thermocline is greater, than the observed. Nevertheless, the model is able to predict ENSO features relatively accurately and bears good resemblance to climatological means.

4.0 DISCUSSIONS AND CONCLUSION

A comparison of pre-European and modern day land surface parameters showed a strong decrease in vegetation fraction, LAI and surface roughness over eastern Australia and southwest Australia, and an increase in albedo for all regions were land cover change had occurred. The direct changes in surface roughness due to the reduction of woody vegetation has increased strength of surface winds by reducing aerodynamic drag (Lawrence 2004), while changes in stomatal resistance has modified surface evaporation, latent and sensible heat fluxes and planetary boundary layer properties (Sellers 1992). The impact of decreased surface roughness is an increase in surface wind strengths and sensible heat fluxes. The increase in near-surface wind amplified the shift from moist northeast tropical air to cooler and drier southeast flow from the Tasman Sea, resulting in the decreased rainfall. Results showed that the regional perturbation of vegetation can possibly magnify the impact of natural mode of individual El Niños, which together with rainfall deficiency, could have a strong impact on climate conditions (e.g. droughts) in eastern Australia. Hence, the replacement of native vegetation with seasonal cropping and improved pastures is likely to be contributing to more severe droughts and increased demand for water.

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