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A continent under stress: interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate

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Abstract

Global climate change is the major and most urgent global environmental issue. Australia is already experiencing climate change as evidenced by higher temperatures and more frequent and severe droughts. These impacts are compounded by increasing land use pressures on natural resources and native ecosystems. This paper provides a synthesis of the interactions, feedbacks and risks of natural climate variability, climate change and land use/land cover change (LUCC) impacting on the Australian continent and how they vary regionally. We review evidence of climate change and underlying processes resulting from interactions between global warming caused by increased concentration of atmospheric greenhouse gases and modification of the land surface. The consequences of ignoring the effect of LUCC on current and future droughts in Australia could have catastrophic consequences for the nation's environment, economy and communities. We highlight the need for more integrated, long-term and adaptive policies and regional natural resource management strategies that restore the beneficial feedbacks between native vegetation cover and local-regional climate, to help ameliorate the impact of global warming.

Keywords: anticipatory policy, climate change, drought, ecosystem collapse, El Niño, land cover change, land surface feedbacks, land use pressures, landscape resilience, tipping points

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Introduction

Global climate change, driven by elevated greenhouse gases such as carbon dioxide, ozone, methane, nitrous oxide and chlorofluorocarbons, has come to prominence in recent years as the major and most urgent global environmental issue (Steffen, 2006; IPCC, 2007). Globally, the combined effect of anthropogenic radiative forcing is estimated to be 1.6 (ranging from -1.0 to $+0.8$) $W\,m^{-2}$ since 1750 (Forster *et al*., 2007). This increased radiative forcing has caused global surface temperatures to rise by approximately 0.76 °C over the past century, being more rapid in the last 50 years (IPCC, 2007). The Fourth Assessment Report (AR4) projects an accelerating increase of global temperature of 2–4.5 °C by the end of 21st century, predominantly due to increasing emissions of greenhouse gasses (IPCC, 2007). However, anthropogenic climate changes may be more rapid and widespread than predicted by the IPCC AR4 (Rahmstorf *et al*., 2007).

Human pressures on the Earth's ecosystems are also accelerating at an unprecedented rate, with almost one-half of global ecosystem production being directed toward human consumption (Vitousek *et al*., 1997; Ramankutty *et al*., 2002; Foley *et al*., 2005). A significant percentage of postindustrial atmospheric CO_2 has come from deforestation resulting in direct radiative forcing of the climate. However, the increased net energy flux from the land surface resulting from deforestation and other forms of land use/land cover change (LUCC) is also an important forcing on global climates over the past 200 years (Betts *et al*., 1996; Foley *et al*., 2003; Brovkin *et al*., 2006). The global estimate of the radiative forcing due to LUCC is -0.2 (± 0.2) $W\,m^{-2}$

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(Forster *et al*., 2007). The climatic impacts of LUCC do not easily translate into the radiative forcing concept used in the evaluation of increased anthropogenic greenhouse gases, thereby increasing the difficulty and uncertainty in quantifying the impacts (National Research Council, 2005). Estimates of global temperature responses from historical deforestation vary considerably with latitude (Voldoire & Royer, 2002; Brovkin *et al*., 2006; Findell *et al*., 2007). Global deforestation since 1750 has mostly occurred in temperate and high latitudes, which produced higher surface albedo resulting in a net cooling effect (Betts *et al*., 2007). In recent decades, however, most deforestation has occurred in tropical and subtropical regions, resulting in reduced evapotranspiration and a net warming effect (Marengo & Nobre, 2001; Li & Fu, 2004). The later process has become more significant than the increased surface albedo, and for this reason, the concept of radiative forcing is not a useful metric of climate change induced by LUCC (Forster *et al*., 2007; Pielke *et al*., 2007).

There have been numerous studies demonstrating that mesoscale (regional) LUCC has resulted in significant perturbations to local and regional climate. Roy & Avissar (2002), for example, highlighted how deforestation in the Amazon modified moisture and heat transfers, which affected regional circulation patterns. Studies also highlight the crucial role of land degradation in tropical African climates, especially the Sahel (Charney, 1975; Foley *et al*., 2003; Paeth & Thamm, 2006). Fuller & Ottke (2002) found that vegetation canopy and structure in west Africa had a greater influence on energy budgets than on short-term rainfall variability, while Los *et al*. (2006) identified a positive feedback between deforestation and changes in Sahel rainfall. Changes were purported to stem from the sinking air masses above the modified land surface to maintain thermal equilibrium, which in turn, led to lower convective potential and a subsequent 20–40% reduction in annual rainfall. Wang (2004) concluded the 20th century drought in Sahel is most likely to have resulted from the interplay of global changes in sea surface temperatures, LUCC and regional climatic feedback due to vegetation dynamics. Held *et al*. (2005) predicted that the anthropogenic drying in the region is partly due to increased aerosol loading and increased greenhouse gases. Therefore, it is more likely that the Sahel, like most regions, functions as tightly coupled ocean–atmosphere–land surface system, whereby external conditions such as sea surface temperatures and LUCC result in alternative wet or dry metastable states (Foley *et al*., 2003).

Like the Sahel, the Australian climate is highly variable and functions as a tightly coupled ocean–atmosphere–land surface system. Two centuries of European land use has left a legacy of widespread transformation and disturbance of Australia's native ecosystems (Hobbs & Hopkins, 1990; McKeon *et al*., 2004). Approximately 15% of the continent has been cleared or severely modified, with this modification concentrated in the intensive land use zone of south-east and south-west Australia. Extensive grazing now covers approximately 43% of the continent and intensive cropping and improved pastures approximately 10%. Much of the extensively grazed area has been affected by episodes of soil and pasture degradation followed by partial recovery, mainly driven by favourable climatic conditions (McKeon *et al*., 2004). Over the last 200 years, most grazed landscapes have experienced a sequence of increased grazing pressure during favourable climatic periods, followed by prolonged drought periods with high disturbance to surface soil and pasture condition. In some cases there has been a resulting vegetation change to increased woodiness. Because of the fragility of the Australian landscape and a highly variable climate, LUCC and land management practices are of critical importance to the future state of Australia's vegetation, soil and water resources.

Australia's economy, especially the agricultural sector, is particularly vulnerable to changes in climate resulting from elevated atmospheric greenhouse gas concentrations, which are likely to further compound existing land use stresses (Hennessy *et al*., 2007). The recent severe and persisting drought conditions in south-east Australia are threatening the collapse of the Murray-Darling River system, which has prompted a US$12.9 billion water plan aimed at its recovery (DEWHA, 2008). Water supplies in most major cities have been affected by recent droughts. Furthermore, the increased stress on the Australian landscape due to continuing drought conditions and land use pressures effectively reduces the potential role of terrestrial ecosystems to sequester greenhouse gases, or in some cases, soils may actually become carbon sources.

This paper provides a synthesis of the interaction, feedbacks and risks of natural climate variability, global warming and land use pressures impacting on the Australian climate. The emphasis is on understanding land surface feedbacks on the nation's regional climate, and the risks for already stressed agricultural and rangeland landscapes. We argue there is a critical need to reassess national climate change and natural resource management policies to include the interactions and feedbacks between the land surface and regional climate, particularly the role native vegetation plays in ameliorating climate extremes and the severity of droughts.

Complex adaptive systems framework

The concept of complex adaptive systems provides a powerful conceptual tool to analyse and reduce the complexity of possible interactions and feedbacks between the land surface and climate through delineating the essential interactions between components that define the characteristics of the system (Pickett & Cadenasso, 2002; Ryan *et al*., 2007). It describes highly dynamic, nonlinear, distributed components that interact through positive and negative feedback mechanisms, which in turn, give rise to the emergence of some new phenomena at other times or geographical scales (Schweitzer, 1997; Levin, 1998).

Landscapes are complex systems which exhibit a high degree of nonlinearity, but despite this, order is maintained through vegetation assemblages that selectively intercept, transform and store solar energy at different rates and times (Wu & Marceau, 2002). Likewise, patterns in native vegetation assemblages across intact landscapes reflect nonlinear feedbacks which emerge as a result of differentiated partitioning of energy and material for a particular biogeochemical cycle (Zalewski *et al*., 2003). This gives rise to a number of potential metastable states for most landscapes depending on historical conditions and current drivers (Gunderson *et al*., 2002).

The spatial heterogeneity and temporal variability of vegetation assemblages may either amplify (positive) or dampen (negative) energy and moisture fluxes within the soil–plant–atmosphere continuum, which in turn, modifies mechanisms that underpin the emergence of mesoscale scale circulation patterns (Nair *et al*., 2007). The conversion of deep-rooted native forests and woodlands to shallow-rooted and seasonally variable exotic crops and pastures modifies land surface properties and their interactions with the atmospheric boundary layer at microscales, and may impact pressure patterns at regional and synoptic scales (Fig. 1). Direct effects include differences in surface albedo and emissivity between native ecosystems and exotic crops and pastures, which modifies the amount of short-wave radiation absorbed and long-wave radiation absorbed and emitted at the land surface (National Research Council, 2005). Indirect effects on net radiation include the ability of the land cover to use the radiation absorbed at the ground surface for partitioning of latent/sensible heat fluxes, and may trigger nonlinear feedbacks on the land surface through state changes in soil moisture and surface hydrology (Rial *et al*., 2004). Nonlinear feedbacks between LUCC and the planetary boundary layer are likely to involve considerable time lags and teleconnections beyond the region of LUCC. These feedbacks can cause climatic systems to rest within any one of a number of possible metastable states or undergo abrupt transitions between them (Rial *et al*., 2004).

In general, land surfaces comprised of trees (woodlands and forests) retain a greater proportion of incoming short- and long-wave radiation than do pastures or crops (Baldocchi *et al*., 2004). Similarly, clearing native forests and woodlands for exotic crops and pastures reduces the amount of moisture available for exchange with the planetary boundary layer (Fig. 1c and d), although crops can increase the moisture flux in the growing season. Actively growing vegetation and moist soils are able to absorb more solar radiation both at the soil surface and at the root zone (Taylor, 2001). Conversely, in dry years, soils tend to have higher albedos and less moisture available for evaporation, which can have a positive feedback yielding a lower rainfall. Pal & Eltahir (2001) suggested that the particular proportions of different land covers at regional scales affects the fraction of precipitation that originates from evaporation and evapotranspiration from within the same region (Fig. 1c). Trenberth (1999) states that this process can add up to 20% of the precipitation occurring over a region, while several locations across the biosphere may actually receive up to 40% from recycled precipitation (Brubaker *et al*., 1993).

The changing Australian climate

During the past two million years, the Australian climate has progressively evolved towards drier and more variable conditions, resulting in an increased dominance of sclerophyllous vegetation and a reduction in the extent of freshwater ecosystems (Kershaw *et al*., 2003). Pollen records from eastern Australia indicate that precipitation 5000–4500 years ago was generally higher than at present, with increased rainfall variability from around 4000 years ago (Schulmeister & Lees, 1995). By analysing coral luminescent data from the Great Barrier Reef as a proxy for rainfall and river flows, Lough (2007) observed that coastal Queensland rainfall and river flows since AD 1661 have experienced strong interannual and decadal variability which is modulated by the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) systems. The record showed good correspondence with observed instrumental rainfall data during the 20th century and indicates increased variability of rainfall and river flows during the last century with more wet and dry extremes than in earlier centuries, a trend consistent with global climate change projections (CSIRO, 2007).

An analysis of historical instrumental climate records shows that Australian climate exhibits substantial variability at the interannual to decadal scales, which is

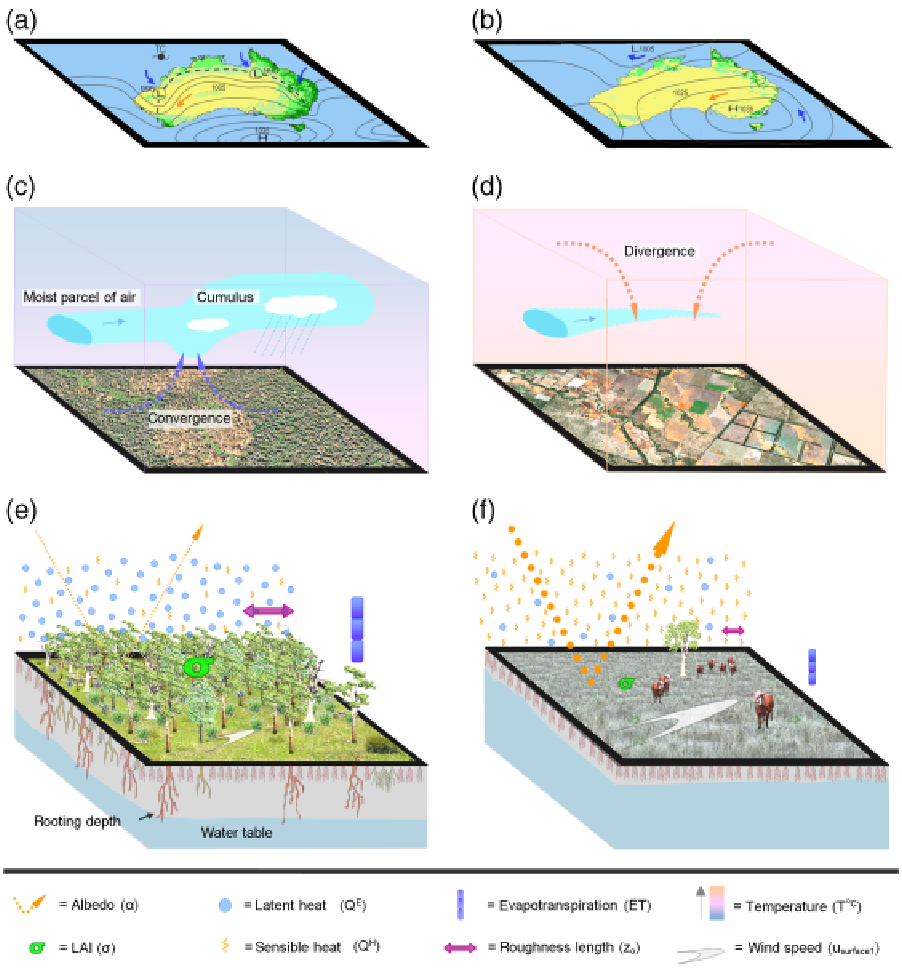

Fig. 1 A schematic model showing the effect of land cover change on the boundary layer properties at the continental scale (a, b), regional scale (c, d) and landscape scale (e, f). The models on left show intact Australian native woodlands, models on the right show feedbacks following clearing. At landscape scale, the major transformations (e → f) include increased sensible heat flux, albedo, and wind speeds. The leaf area index (LAI), vegetation fraction, evapotranspiration, latent heat flux, surface roughness and soil moisture have decreased. At the regional scale, these changes in fluxes alter the feedbacks to broader exchange of moisture between the land surface and the boundary layer, and regions of forced convection and advection (c → d), which in many cases have contributed to decreases in cumulus cloud formation. The potential for cumulative effects of regional changes in land cover on pressure systems are shown schematically as Δ isobars (a → b). Artwork by Justin Ryan.

strongly influenced by ENSO and PDO (Power *et al.*, 1999; Nicholls, 2006; Power & Smith, 2007). Some of the driest years such as 1902, 1972, 1982 and 2002, were associated with El Niño events, while the very wet years such as 1973, 1974, 1999 and 2000 were associated with La Niña events. Exception to this high interannual variability resulting from ENSO are extended periods of above and below average rainfall which can last several years such as the Federation (1896–2002) and Millennium (2001–2007) droughts (McKeon, 2006). The cause(s) of these extended dry periods are still not well understood, but may be due to synchronicity in individual El Niño years coupled with quasidecadal and interdecadal fluctuations in sea surface temperatures and mean sea-level pressures (Power *et al.*, 1999; White *et al.*, 2003).

Australian annual mean surface air temperatures have risen by about 0.9 °C since 1910. The first half of the 20th century experienced very little trend in temperature, however since 1950 a warming trend of 0.16 °C decade^{-1} has occurred (CSIRO, 2007). South-east Australia has experienced persistent dry conditions and well above average temperatures during the last decade (Fig. 2a and b) (Smith, 2004; Hope *et al.*, 2006; Nicholls, 2006). Smith (2004) showed an increase in rainfall in the north and north-west of Australia and a widespread decrease in eastern Australia for recent decades.

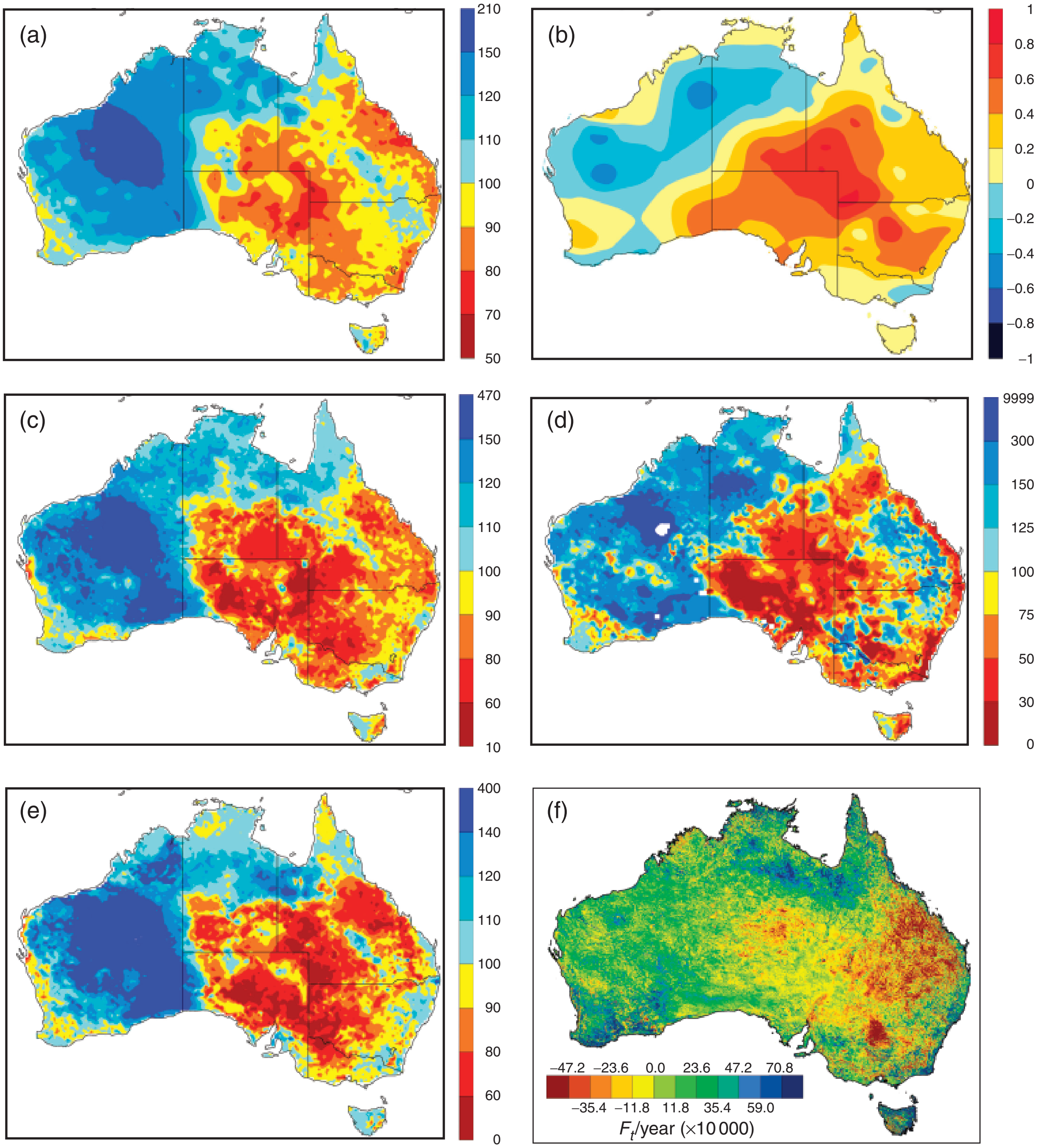

Fig. 2 Observed and simulated anomalies in annual (a) rainfall, (b) mean surface temperature, (c) soil moisture in upper 1 m profile, (d) potential flow to stream (e) pasture growth and (f) observed changes in vegetation fractional cover over 1981–2006 (Donohue *et al.*, 2008, 2009). For (a) to (e), the anomaly is calculated for 1993–2006 with the period 1970–1992 assumed to represent the long-term 'normal' conditions.

Since the late 1970s, the frequency of El Niño events often associated with eastern Australian droughts has increased (Power & Smith, 2007). Nicholls (2004) demonstrated that droughts in south-east Australia are characterized by higher temperatures and prolonged heat waves, postulating a relationship between droughts and global warming. These trends suggest that the relationship between Southern Oscillation Index and Australian-wide temperature and rainfall is changing (Nicholls *et al.*, 1997; Power *et al.*, 1999; Power & Smith, 2007).

The drying phenomena in eastern Australia can be partially explained by differences in large-scale synoptic systems resulting from changing tropical circulation patterns. According to Vecchi *et al*. (2006), the recent increase in the frequency of El Niño events has stemmed from a weakening of the zonal overturning of tropical air masses commonly known as the Walker circulation. Using observational data and modelling experiments, Vecchi *et al*. (2006) showed that this phenomena has been caused by warming tropical sea surface temperatures driven by increasing greenhouse gases concentrations, which in turn, alters the thermal structure and circulation of the tropical Pacific. The tendency for long-term weakening of the Walker circulation in response to a warming climate was also shown by Vecchi & Soden (2007) to be a fairly robust characteristic of IPCC AR4 climate models. It is therefore likely that global warming is affecting climate in the eastern Pacific, where ENSO historically has been responsible for at least part of the climate's variability. Consequently, past experiences of ENSO impacts have probably become a less accurate guide to the future climate of eastern Australia (Power & Smith, 2007).

In addition to the systematic weakening of Walker circulation, Lu *et al*. (2007) showed that the circulation of Hadley cells, particularly the subtropical cell (dry zone), have also weakened and moved poleward. Fu *et al*. (2006) estimated the Hadley cell has widened by approximately 2° latitude for the period 1979–2005, while Seidel & Randel (2007) suggest an expansion of 5–8° latitude during the same period. This expansion may be attributable to factors other than the greenhouse gas-induced global warming, such as ozone depletion and/or natural climate variability (Lu *et al*., 2007). Recent research also suggests that Asian aerosols are increasing monsoonal rainfall in north-west Australia (Rotstayn *et al*., 2008). While this work requires further attribution, it raises important questions about the influence of other forcings in addition to elevated anthropogenic greenhouse gases on Australia's climate

The importance of step or abrupt changes in climate and its inclusion in climate change adaptation strategies has been increasingly emphasized in the last decade (Narisma *et al*., 2007). In the Australian context, step changes in rainfall and the impact on water resources have been a major topic of research and focus of policy makers (Cai & Cowan, 2008a). In south-west Western Australia, there was a step decline in winter (May–July) rainfall during the mid-1970s by $\sim 15\%$, resulting in reduction in inflow to water storages in the region by $>50\%$ (Bates *et al*., 2008). In Victoria during the past decade, there has been a 50% reduction in autumn and a 10–15% reduction in winter rainfall (Cai & Cowan, 2008a). A combination of dry soils during autumn and reduction of rainfall during the wet season (winter) resulted in unprecedented decline in water availability in the Murray River system. The full ecological impacts have not been assessed, although recent commentary suggests that the lower Murray-Darling is on the brink of irreversible collapse. Similarly, central and south-east Queensland have experienced very strong rainfall reductions during recent decades, and in particular for the period 2001–2007 (QCCCE, 2007).

Increased temperatures in south-east Australia are contributing to hotter droughts, which is further reducing runoff volumes (Cai & Cowan, 2008b). While these reductions in rainfall are likely to have multiple causes, increasing anthropogenic CO_2 is frequently cited as the major contributor. Global warming is resulting not only in warmer and drier average climate conditions in Australia, but also is contributing to a more frequent extremes such as more severe and prolonged droughts, heatwaves, bushfires and floods. This is demonstrated by the devastating bushfires which swept Victoria on ninth February 2009 driven by temperatures $>45\,^\circ\mathrm{C}$ and winds in excess of $90\,\mathrm{km\,h^{-1}}$, causing extensive loss of life and property.

The Australian continent is likely to experience further warming of 0.6–1.5 °C by 2030, increasing to 1.0–5.0 °C by 2070 (CSIRO, 2007). As may be expected with increased warming, the number of hot days that exceed 35 °C for many locations throughout Australia is projected to increase substantially. Likewise, the number of days $<0\,^\circ\mathrm{C}$ is expected to decrease.

The projected precipitation changes from the IPCC AR4 show a consistent decrease in rainfall along the southern part of the Australian continent during the winter season. There is less agreement in the sign of rainfall change in eastern Australia during the summer season when all 23 IPCC AR4 models are considered (IPCC, 2007). The regional rainfall change projections of CSIRO (2007) indicate a rainfall change in the range of 0% to -10% by 2030 and $+5\%$ to -30% by 2070 for southern Australia with the strongest decline in winter–spring. The projected rainfall changes in eastern and northern Australia show a projected change of $+5\%$ to -10% by 2030, and even greater range of $+20\%$ to -30% by 2070 (CSIRO, 2007). However, the projected rainfall changes for eastern Australia show stronger rainfall declines when the more reliable climate models are selected and the poorly performing models are discarded (Smith & Chandler, in press).

Projected rainfall changes indicate that a large area of the continent will experience a strong increase in the frequency of dry days and very wet days (i.e. 90th percentile). Using the output from the models used for the AR4 (IPCC, 2007), Mpelasoka *et al*. (2007) computed a soil–moisture-based decile drought index. They show that by 2030 the frequency of droughts will increase 20–40% over eastern Australia compared with

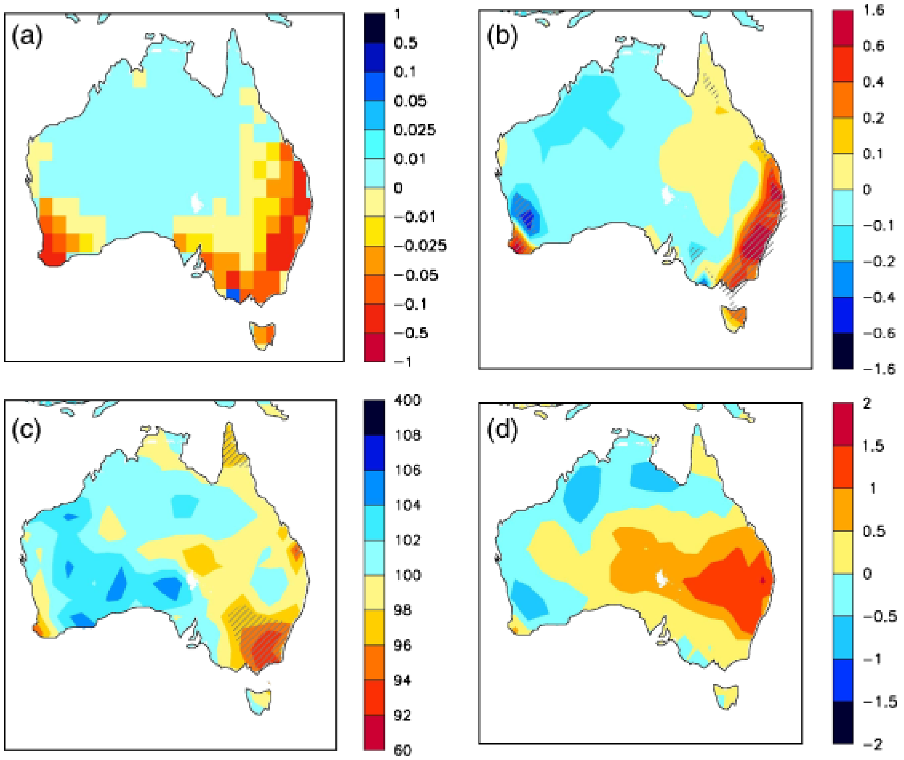

Fig. 3 (a) Land cover map showing woody vegetation fraction change (dimensionless) used in the CSIRO climate model; (b) mean surface temperature changes (°C) during November–March, (c) mean annual precipitation change (%) during November–March and (d) model simulated difference (November–March) surface temperature (°C) during November–March for the 2002/2003 El Niño drought. For (a–c), the simulated changes are shown over the period 1951–2003. (modified from McAlpine *et al.*, 2007).

1975–2004. This would have major negative consequences for agriculture, natural resource management, drought relief payments, river systems and water resources, bushfire frequency, and biodiversity conservation. These changes reflect conditions experienced in eastern Australia over the past decade (Fig. 2).

Land cover change and land use pressures

Two hundred years of European settlement has transformed the Australian continent (Hobbs & Hopkins, 1990). Within the intensive land use zone of south-east and south-west Australia, approximately 50% of native forests and 65% of native woodlands have been cleared or severely modified (Barson *et al.*, 2000). South-east Australia was progressively cleared during the 19th century and first half of the 20th century, with many landscapes now retaining <10% native vegetation cover. The transformation of the sheep-wheat belt of south-west Western Australia began in the 1890s but accelerated after World War II (Allison & Hobbs, 2006). Since World War II, over 13 million ha of native vegetation were cleared in this region mainly for cultivation of winter crops (Ray *et al.*, 2003). In both south-east and south-west Australia, clearing of native vegetation has triggered rising groundwater levels and major salinity problems (Gordon *et al.*, 2003). Active revegetation programs funded by Commonwealth and State governments have been implemented in recent decades to address salinity problems in these regions.

Despite a decline in the relative importance of agricultural commodities to the Australian economy since 1960, recent satellite monitoring indicates that LUCC is still highly active, with Queensland the most affected region (Fig. 3a) (Seabrook *et al.*, 2006). The clearance of native vegetation in Queensland peaked at over 500 000 ha yr^{-1} between 2000 and 2004 (Seabrook *et al.*, 2006), mainly for beef cattle pastures. This ranked the region fifth worldwide on deforestation rate (Lepers *et al.*, 2005). Unlike south-east and south-west Australia, however, the subtropical and tropical forests and woodlands of Queensland are able to regenerate naturally through vegetative means, hence avoiding the need for expensive manual revegetation programs.

In recent decades, the deforestation of the Australian landscape has been compounded by increased and sustained land use pressures arising from a steadily growing human population, rapid economic growth

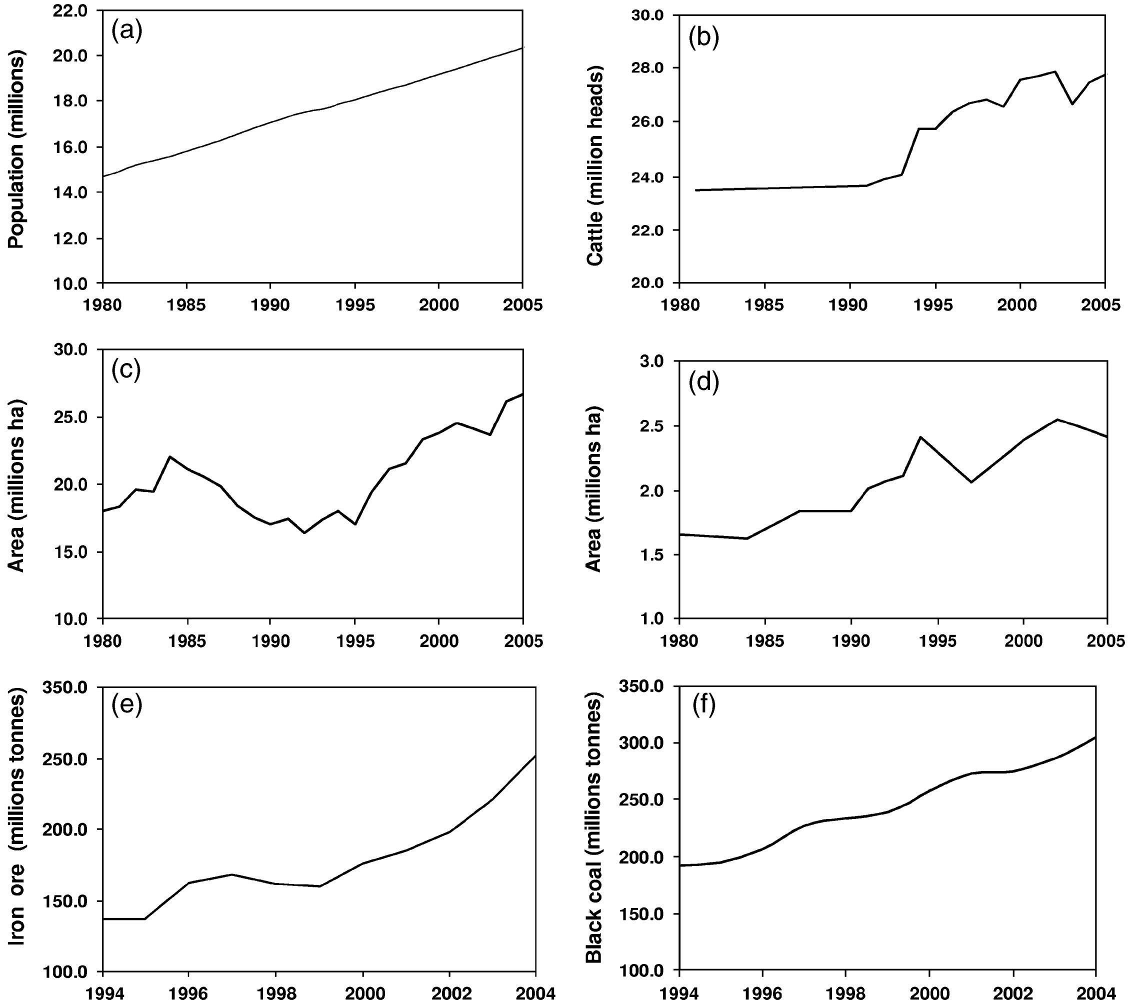

Fig. 4 Trends for the Australian continent for: (a) total human population; (b) cattle herd numbers; (c) area of dry land cropping; (d) area of irrigated cropping; (e) total iron ore production and (f) total black coal production. Data sourced from Australian Bureau of Statistics.

and rising global demand for Australian commodities, especially mineral and energy exports (Fig. 4). Dryland and irrigated agriculture that was traditionally concentrated in the intensive land use zone, has expanded into marginal semiarid regions of eastern Australia, with irrigated cotton farming causing intense water resource allocation debates. Mineral and energy resource exports are the major driver of recent strong economic growth, with iron ore production increasing by 85% and black coal production by 60% since 1994 (Fig. 4). Australia is the world's largest exporter of black coal and second for iron ore. The spatial footprint of mining, although smaller than cropping and grazing, is having a significant impact on the landscape in mining regions and beyond through economic and population growth.

There are also pressures on the extensive rangelands. Grazing is the major land use on over 40% of the continents rangelands (White *et al.*, 2003), with 80% of this occurring in the state of Queensland. Foran (2007) comments that the sustainable management of rangeland landscapes continues to be outpaced by the need for growth, droughts, personal gain and invasive species. For example, when landholders maintain grazing pressure on land affected by drought, the resilience of the landscape is decreased to such an extent that recovery following rains does not occur and the landscape becomes progressively degraded (McKeon *et al.*, 2004). From a grazing industry perspective, land and pasture degradation are seen as the loss of desirable perennial grasses and shrubs resulting in increased soil erosion (both wind and water driven), soil structural decline (loss of infiltration capability) and the infestation of woody weeds (Stafford-Smith *et al.*, 2007). These processes are traditionally quantified in the terms of loss of pasture production and hence livestock carrying capacity. Meanwhile, the effects on albedo, surface energy balance and surface roughness from vegetation cover change in the rangelands remain largely unconsidered. Sturman & McGowan (2009) highlighted that clay pans (playas) in central Australia were significant sources of sensible heat flux, and have considerable impacts on air temperature, convective processes and wind regimes at micro to regional scales. It is likely therefore that loss of ground cover due to drought and overgrazing will have a similar effect on energy fluxes and convective processes.

Empirical evidence suggests that rainfall variability in the absence of pasture burning is a major driver of dynamics of woody vegetation cover across the continent. At 30 long-term monitoring sites in Queensland, Burrows *et al*. (2002) recorded an increase in the basal area of woody vegetation from 1.06 to 11.86 $\pm$1.38 (SE) $m^2\,ha^{-1}$ over a 14-year period. This was attributable to a reduction in pasture burning in grazing lands. Fensham & Holman (1999) and Fensham & Fairfax (2005) recorded evidence of locally occurring tree death in eucalypt and acacia woodlands in the same region attributed to the increased competition for soil moisture during drought. In south-west Queensland, the extreme drought experienced from 2001 to 2006 resulted in substantial death of long-lived perennial grasses, trees along watercourses and extensive areas of understorey native shrubs (Hassett *et al*., 2006). In the rangelands of Western Australia, rangeland monitoring data shows an increase in tree and shrub populations across the arid shrublands where the rainfall for the period 1996–2000 was 60% above-average rainfall (Watson *et al*., 2007). The authors concluded that the negative impact of grazing was less than the positive impact of rainfall over the period of measurement for the whole region, although there was some evidence of adverse grazing impacts.

These contemporary LUCCs are reflected in changes in the vegetation fraction for the Australian continent for the period 1981–2006 derived from Advanced Very High-Resolution Radiometer reflectance data (Donohue *et al*., 2008, 2009) (Fig. 3d). For the Australian continent, the study showed the total vegetation fraction (F_t) increased by 0.021 or 9% over the period. However, there was considerable regional variation, with eastern Australia experiencing a general decrease in F_t while northern and Western Australia experienced an increase. Changes in fire and rainfall regimes and potential CO_2 fertilization effects were identified as possible causes (Donohue *et al*., 2008, 2009).

A major uncertainty in attributing causes to changes in perennial land cover (trees and shrubs) results from the number of interacting factors involved (CO_2, grazing management, frequency of pasture burning and wild fires and severity of intermittent drought). While many of the effects on rangelands have been well documented nationally (Noble, 1997a, b; Dyer *et al*., 2001) and internationally (Scholes & Archer, 1997), the effects of increasing CO_2 on tree/grass balance are just beginning to be studied, particularly for the tropical C_4-dominated grasslands of northern Australia (e.g. Stokes *et al*., 2005). If C_3 woody plant species are favoured over C_4 grasses (in the absence of fire), then increasing CO_2 would be expected to be contributing to processes of woodland thickening and perennial land cover increase (Morgan *et al*., 2007), provided similar rainfall regimes are maintained (Fensham *et al*., 2009). The effects of CO_2 on reduced transpiration and consequences for landscape-scale temperature and humidity, however, also need to be determined (Pollard & Thompson, 1995; Morgan *et al*., 2004) to fully quantify indirect CO_2 effects on regional climate.

Evidence of regional climatic impacts of land cover change

Changes to Australia's LUCC described above translate into significant changes in land surface parameters, and therefore represents an important additional influence on Australia's climate. To date, the major research emphasis of LUCC feedbacks on the Australian climate has been on the historical conversion of native vegetation to cropping and exotic pastures (Pitman *et al*., 2004; Pitman & Narisma, 2005; McAlpine *et al*., 2007). The climate impacts of contemporary changes in land use, and vegetation cover in the rangelands, has yet to receive detailed analysis.

The most prominent observation evidence of land cover change impacting climate has been the effect of cropping vs. native vegetation along 750 km Bunny fence in south-west Western Australia. This work provides measurements of the effect of clearing woody native vegetation on surface albedo, surface roughness, latent and sensible heat fluxes (Shukla *et al*., 1990; Meher-Homji, 1991; Lyons *et al*., 1993; Segal *et al*., 1998), and the preferential formation of cumulus clouds over the vegetated lands (Lyons, 2002; Ray *et al*., 2003). The analysis of observational satellite data by Nair *et al*. (2007) showed that a 50% replacement of native vegetation by winter crops in south-west Western Australia resulted in a decrease of $\sim 7\,W m^{-2}$ in short-wave radiative forcing, with the strongest effect during the fallow season.

Several studies have modelled the potential impact of land cover change on Australia's climate. Narisma & Pitman (2003) used four ensemble simulations (January and July) to demonstrate a strong impact of land cover change on surface temperatures in the south-east, south-west and north-east of the continent and a reduction in rainfall of $\sim 1\,\mathrm{mm\,day^{-1}}$ over south-west Australia. Pitman *et al*. (2004) demonstrated a reduction in rainfall in south-west Western Australia coincided with local areas of land cover change and reduced surface roughness.

To evaluate the impacts of historical land cover change on the Australian regional climate (Fig. 3a), McAlpine *et al*. (2007) conducted two sets of model experiments comparing the climatic impacts of modern day (1990) vs. pre-European land cover conditions. They used the same model as used in Australia's contribution to the IPCC 4AR (CSIRO Mark 3 atmospheric GCM), while high-resolution vegetation parameters and soil characteristics derived from the latest satellite images and GIS data (see P. Lawrence, 2004, unpublished data; for details of land surface parameter mapping and data integration into the CSIRO GCM). The experiments consisted to two simulations of a 10 model ensemble for the period 1949–2003, one for the pre-European conditions and one for the modern day conditions. There was a statistically significant warming, especially during the extended Austral summer (November–March) for mean surface temperature by 0.1–0.6 °C in eastern Australia and a cooling of 0.1–0.4 °C in south-west Western Australia (Fig. 3b). The mean summer rainfall showed a statistically significant decrease by 4–12% in south-east Australia (Fig. 3c). The changes in surface temperature were more coincidental with areas of land cover change than the rainfall. In addition, the analysis showed land cover change contributed to hotter summer temperatures during El Niño years, such as the severe drought of 2002/2003 (Fig. 3d).

Below, we use data from the experiments reported in McAlpine *et al*. (2007) and Syktus *et al*. (2007) to derive regionally averaged values of mapped surface parameters for pre-European and modern-day land cover characteristics and the corresponding changes in regional climate over eastern New South Wales (summer) and south-west Western Australia (winter) (Fig. 5; supporting information, Table S1). Although these findings are model based rather than empirical evidence, we are confident our results are robust because of the accuracy of the vegetation and land surface characteristics used in the CSIRO GCM, and the large ensemble size and integration period of 53 years forced with prescribed sea surface temperatures. Furthermore, the model results are statistically significant using bootstrap Monte-Carlo statistical procedures. They provide a reference point for future modelling experiments and observational data assessing the impact of land cover change on regional climate in terms of changes to energy balance and other land surface characteristics. Furthermore, these results can be used to compare the impact of LUCC with other forcings such as aerosol or greenhouse gas forcings.

During the summer season in eastern New South Wales, the area-averaged changes in surface characteristics (Fig. 5a) showed large decreases in vegetation fraction (19%) and LAI (23%), and a resulting 7% increase in albedo. A corresponding reduction in surface roughness (46%) coincided with a 9% increase in wind speed, while summer surface temperatures exhibited an average warming of $\approx 0.6\,^{\circ}\mathrm{C}$. This warming was related to an increase in surface absorption of incoming short-wave radiation by 5.2%. The area-averaged rainfall decreased by 5.2%. The area-averaged energy fluxes showed a reduction in latent heat flux (7.3%) and an increase in sensible heat flux (1.3%).

During the winter season in south-west Western Australia, replacing native woodlands with predominantly winter crops resulted in a modest decrease in vegetation fraction of 5% and LAI of 12% (Fig. 5b). The stomatal resistance decreased by 15%, surface albedo increased by 14%, while surface roughness decreased by 35%. The strong increase in surface albedo is a combination of vegetation changes and bright sandy soils characteristic of this region. Conversion of native vegetation to winter crops changed the Bowen ratio, as evidenced by a small increase in latent heat flux and a 12% decrease in sensible heat flux, which was opposite to changes in east New South Wales. The surface temperature decreased by 0.14 °C with a small increase in rainfall.

The impact of land cover change in south-east Australia was larger than in south-west Western Australia as evident from changes to surface temperature and precipitation (Fig. 3). The simulated rainfall reduction in summer rainfall southern New South Wales extending into Victoria of $>5\%$ for modern land cover conditions is not insignificant when compared to observed changes (Cai & Cowan, 2008a, b). In south-west Western Australia, multiple factors, in addition to land cover change, appear to be impacting the regional climate (Nicholls, 2006).

Risks resulting from interactions among natural variability, global warming and LUCC

Australia's natural resources and agricultural sector are particularly vulnerable to climate change, especially from an increased frequency of severe droughts (Hennessy *et al*., 2008). The risks of ignoring the role of land surface feedbacks in current and future droughts are potentially catastrophic for Australia's environment, economy and communities. Climate

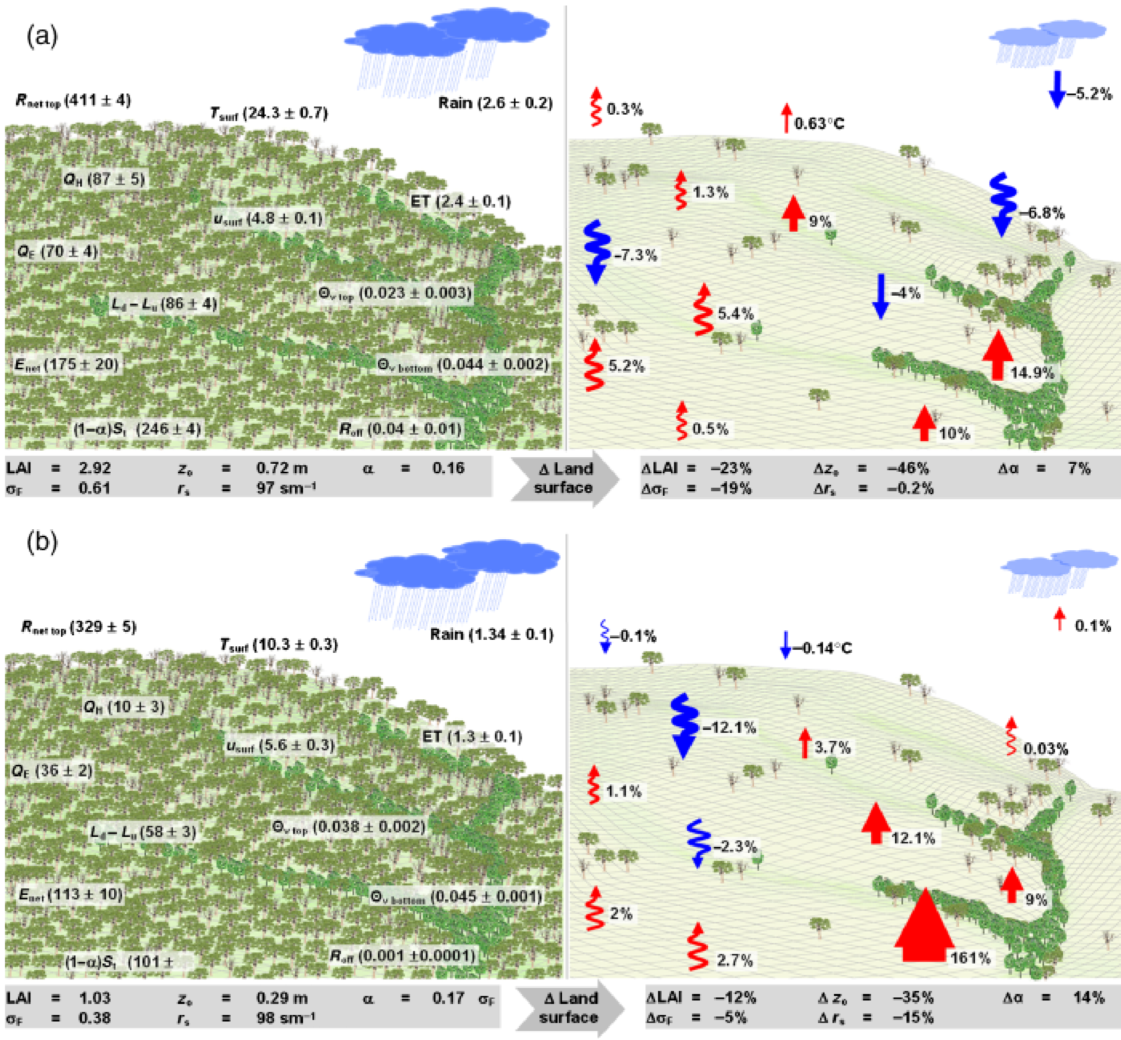

Fig. 5 Two hypothetical ecosystems showing: (a) the DJF (Austral summer) for eastern New South Wales; and (b) JJA (Austral winter) for south-west Western Australia. Left: a preclearing (natural) ecosystem with the initial land surface properties/fluxes with natural vegetation (bottom box) and corresponding climate responses (labels on landscape model); right: changes in land surface properties/fluxes due to clearing (bottom box) and corresponding climate responses (labels on landscape model) in a present-day-modified landscape. Note: blue arrows (decreases), red arrows (increases), arrow width relative to magnitudes of change. α, surface albedo; LAI, leaf area index; σ_F, vegetation fraction; z_0, surface roughness; r_s, stomatal resistance; T_{surf}, surface temperature; Rain, rainfall; Q_H, sensible heat flux; Q_E, latent heat flux; $L_d - L_u$, net surface long-wave radiation; $(1-\alpha)S_t$, net surface short-wave radiation; E_{net}, net surface energy; $R_{net\ top}$, net radiation at top of atmosphere; u_{surf}, surface windspeed; ($\theta_{v\ top}$, $\Theta_{v\ bottom}$), top and bottom layer soil moisture and ET, evapotranspiration rates. Artwork by Justin Ryan.

changes due to increased anthropogenic greenhouse gases coupled with land surface feedbacks appears to be amplifying the natural climate variability and has the potential to tip Australia's climate, especially in south-east Australia, into a new regime of more extensive, frequent and severe droughts. The term 'tipping' refers to a critical threshold at which a small change in the control parameters can alter the state of the climate system (Lenton *et al.*, 2008). The combined effect of transient increases in greenhouse gases and pressures from LUCC may already be contributing to more severe droughts for eastern and southern Australia (Nicholls, 2004), and is an ominous sign for the increased incidence and severity of projected future droughts (Mpelasoka *et al.*, 2007; Hennessy *et al.*, 2008).

Irrespective of whether climatic changes are gradual or abrupt, a transition to a hotter and more drought-prone climate represents a major risk for Australia, particularly if changes are beyond the capacity of environmental and production systems to recover or adapt. The Murray-Darling Basin is already at risk of environmental collapse due to the combined stressors of land use intensification and climate changes. Declining inflows due to persisting drought conditions are triggering conflict between human and environmental uses of water. Cai & Cowan (2008b), in a study of the effect of rising temperatures on the climatological inflows of Murray-Darling Rivers, suggests that a 1 °C rise in temperatures would reduce river inflows by $\sim$15% of their present levels. Even more alarming, a warming of 2 °C would reduce inflows by up to 30%, further exacerbating the effect of predicted rainfall decline.

Restoring freshwater environmental flows in the Murray-Darling Basin is a complex economic and environmental problem, of which native vegetation is part. The clearing of native forests and woodlands generally increases runoff volume (Bonan, 2002). However, the strong feedbacks of deep-rooted native vegetation on regional climate in south-east Australia highlights the need to recognize its broader role in the hydrological system, including the formation of rain-bearing convective systems through the addition of considerable amounts of moisture and convective energy to the boundary layer (Anthes, 1984). Gordon *et al.* (2003) estimate that the replacement of native vegetation with annual crops and pastures has caused a $\sim$10% decrease in water vapour flux from the continent, corresponding to an annual freshwater flow of almost 340 km^3. This highlights the need to broaden the scope of freshwater management in Australia to include the hydrological functions of deep-rooted native vegetation at the mesoscale rather than focusing on runoff differences for a pair of small vegetated and cleared catchments.

Native ecosystems and biodiversity are also at risk. The cumulative impact of 200 years of landscape fragmentation, droughts, grazing disturbance and invasive species has diminished the resilience of Australian ecosystems. Loss of ecosystem resilience (Walker & Salt, 2006), in turn, often paves the way for a switch to an alternative ecosystem state (Scheffer *et al.*, 2001). A shift to a more arid, drought-prone climate in south-east Australia arising from the synergistic effects of land cover change and elevated greenhouse gases are likely to change vegetation dynamics. This includes a potential decline in tree foliage cover, increased risk of catastrophic death of native trees (Fensham *et al.*, 2009) and amplification of the feedbacks between the land surface and regional climate. These risks need to be assessed against potential effects of increased atmospheric CO_2 on woody plant growth, stomatal resistance and transpiration rates (Pollard & Thompson, 1995; Morgan *et al.*, 2004).

Australia's agricultural sector is also at risk. Australia is a large producer and exporter of food and fibre (Stokes *et al.*, 2008). The capacity of agriculture to sustain agricultural production is already at major risk in the lower Murray-Darling Basin as evidenced by the collapse of the rice harvest, with production falling from 1.75 million tonnes in 2001 to 20 000 tonnes in 2008 ($-$98.9%). Substantial declines are also occurring in wheat and irrigated cotton production. An increased frequency of severe droughts is impacting the condition of rangelands and better adaptive grazing and fire management regimes need to be implemented (Stafford-Smith *et al.*, 2007). Climate change, drought and water security are now the major foci of environmental policy in Australia. This is exemplified by the US$12.8 billion water resources plan, rising farm debt and the estimated US$3 billion of national government funds spend on drought subsidies since 2001. However, there is still little recognition by policy makers and research community of the close coupling of the human-modified land surface and the atmosphere (sensu Pielke *et al.*, 2007).

Policy implications

The evidence provided here can be considered in the wider context of policy decisions affecting Australian land use and land cover. It provides a basis for including LUCC in climate risk management analyses by documenting the previously ignored feedback of the land surface on regional climate. Such analyses is useful to inform policy development in terms of balancing the beneficial effects of increased deep-rooted woody vegetation cover (in terms of climate, salinity risk, resilience, biodiversity, carbon storage) against higher costs (in terms of loss of land available for agriculture and human settlement).

To date, Australia's policy response to climate change has focused on mitigation and adaptation of the impact of climate change due to elevated greenhouse gas concentrations (Garnaut, 2008). The overview of interactions, feedbacks and risks of LUCC presented here highlights the need to include the management of the Australian land surface as an additional mitigation and adaptation strategy to climate change (Stafford-Smith *et al.*, 2007). Policy makers frequently are failing to see that climate change is a multidimensional issue where multiple effects and their interactions need to be considered simultaneously. Carbon offsets (e.g. carbon credits, tree plantations, green fleet schemes) are used to justify business as usual, while the biophysical and ecohydrological functions of whole landscapes are being ignored. As Walker & Salt (2006, p. 14) highlight, 'By understanding how and why the system as whole is changing, we are better placed to build capacity to work with change, as opposed to being a victim of it'. The time scale of policy also needs to expand. Historically,

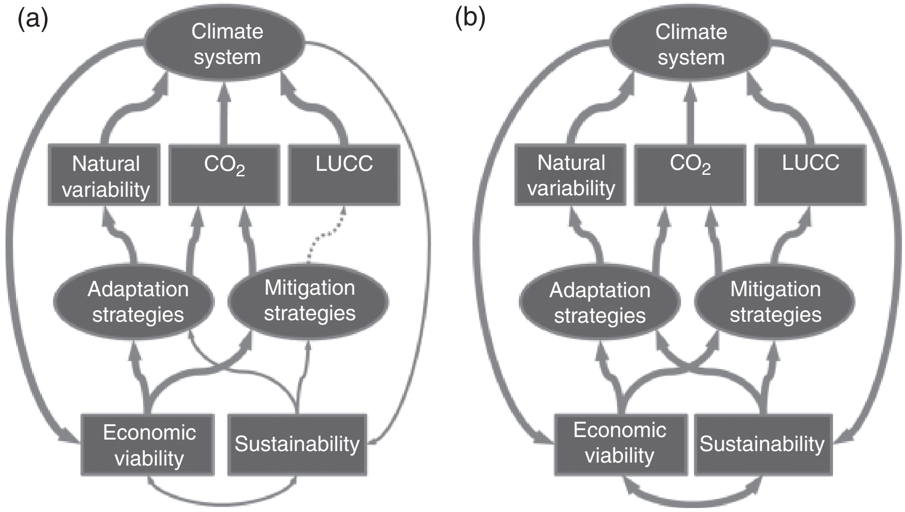

Fig. 6 A conceptual model showing two policy perspectives of key forces impacting on the Australian climate system: (a) the current policy perspective, where most emphasis is placed on tolerating natural climate variability, economic viability and adapting to increased CO_2 levels; has moderate emphasis on environmental sustainability, but largely ignores the feedbacks of LUCC (smaller/dashed arrows); and (b) an alternative policy perspective which recognizes the role of LUCC in the climate system and has a strong emphasis on environmental sustainability.

policy and land management cycles have been a short-term reaction to drought and economic hardship (Stafford-Smith *et al.*, 2007).

Recognizing the problem is the first step towards a solution (Bell, 2006). Recognition involves adopting a broader, holistic perspective on climate change which includes multiple processes and feedbacks (including CO_2) impacting on Australia's regional climate. This requires a new paradigm which recognizes the tight coupling of the land surface and Australia's regional climate within an anticipatory policy and management framework (Fig. 6). Anticipatory rather than reactive policies are one of the preconditions for mitigating and successful adaptation to dangerous climate change (Smith, 1997). Anticipation requires recognizing the risks and uncertainties of climate change and evaluating decision options under uncertainty as a foundation for strategic policy making. The ground rules for managing Australia's natural resources and landscapes are changing rapidly (Campbell, 2008). Scientists need to actively inform this process so as to ensure sustainable win–win–win solutions for land and water resources, biodiversity conservation, rural communities and the agricultural sector (sensu Bell, 2006).

Reducing greenhouse gas emissions is essential but not sufficient as a climate change mitigation strategy. Anticipatory policies need to be explored and tested aiming at reduction in land use pressures and restoration of native vegetation cover in order to try to avoid likelihood of irreversible climate change. Potential mitigation and adaptation options include: (1) tighter legislative controls on the clearing of native vegetation, including regrowth native vegetation in previously cleared subtropical landscapes; (2) expanded investment in ecological restoration based on the strategic integration of native vegetation with production systems in the highly modified agricultural landscapes; (3) an evaluation of the long-term viability of marginal cropping and grazing lands and their vulnerability to soil and vegetation degradation; and (4) adaptive management of stocking rates according to climate conditions. Integrated climate change mitigation/amelioration and landscape restoration strategies need to be urgently developed and tested. Successful implementation could lead to increased ability of the Australian landscape to buffer against climate extremes driven by increased concentrations of greenhouse gases. Such strategies could provide win–win situations for farmers where increased native woody vegetation on farms would result in greenhouse gas sequestration (including $ for green carbon credits) and restoration of the beneficial feedbacks between the land surface and Australia's regional climate.

Conclusion

This paper demonstrates the significance of LUCC for the climate of Australia, and the vitally important need for it to be explicitly considered in climate change mitigation policies and planning processes. The historical clearing of approximately 15% of the continent for agriculture is likely to have contributed to a hotter and drier climate and exacerbated the effect of the El Niño by increasing the severity of droughts, especially in south-east Australia. This problem is being compounded by the interaction of contemporary land use pressures and an emerging trend towards a hotter and more-drought-prone climate driven by increased anthropogenic greenhouse gases. The large-scale restoration of native ecosystems has the potential to ameliorate regional climate change while providing other ecological services such as biodiversity, clean air and water; however, we currently do not know to what extent such actions will modify temperature and rainfall patterns directly. This question requires urgent consideration to inform regional planning processes that lead toward more integrated climate mitigation and sustainable land use outcomes.

A number of lessons can be drawn from this paper that have wider implications beyond Australia:

1. The current global climate change agenda needs to recognize that climate change is a multidimensional issue, and that LUCC must be included in global and regional strategies to effectively mitigate climate change (sensu Feddema *et al*., 2005; Pielke, 2005).
2. A coordinated research effort is required to address the multidimensionality of climate change, including the role of LUCC and its dynamic interaction with increased concentrations of anthropogenic greenhouse gases. This requires evaluating:

(i) the capacity of reforestation to ameliorate the impact of climate change at a regional scale; and
(ii) if so, how much vegetation is required and where it should be located?

3. Reducing deforestation in the tropics and subtropics needs to be a global priority. This requires a strong and coordinated global and regional effort through a combination of regulatory frameworks and well-constructed carbon markets to halt deforestation and actively facilitate reforestation. This would have additional benefits for a wide array of ecosystem services that underpin environmental sustainability.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. The mean changes in area-averaged surface energy fluxes (absolute and *% change*) and corresponding climate variables, between pre-European and modern-day land cover conditions. Changes were derived from a 10-member ensemble of modelling experiments (McAlpine *et al*., 2007). *Legend*: Latent Heat (Q_H); Sensible Heat (Q_E); Shortwave Radiation at Surface ($(1-\alpha)\ S_t$); Shortwave Radiation at Top of Atmosphere (αS_t); Longwave at Surface (L_d-L_u where L_d is downward and L_u is the upward radiation flux); Net Surface Radiation ($(R_n) = (1-a)\ S_t + (L_d-L_u)$; Net Radiation at Top of Atmosphere, (R_{nt}); Net Surface Energy $(E_{net}) = (1-\alpha)\ S_t + (L_d-L_u)-(Q_E + Q_H)$; α = surface albedo. *Units*: (Q_E, Q_H, S_t, L_d, L_u, R_n, R_{nt}, E_n): Wm^{-2}; (T_{surf}): °C; (u_{surf}): ms^{-1}; (Rain, ET): $mmday^{-1}$; (Θ_v and α): dimensionless.

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