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Little left to lose: deforestation and forest degradation in Australia since European colonization

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Abstract

Aims

Australia is among one of the world's wealthiest nations; yet, its relatively small human population (22.5 million) has been responsible for extensive deforestation and forest degradation since European settlement in the late 18th century. Despite most (~75%) of Australia's 7.6 million-km^2 area being covered in inhospitable deserts or arid lands generally unsuitable to forest growth, the coastal periphery has witnessed a rapid decline in forest cover and quality, especially over the last 60 years. Here I document the rates of forest loss and degradation in Australia based on a thorough review of existing literature and unpublished data.

Important Findings

Overall, Australia has lost nearly 40% of its forests, but much of the remaining native vegetation is highly fragmented. As European colonists expanded in the late 18th and the early 19th centuries, deforestation occurred mainly on the most fertile soils nearest to the coast. In the 1950s, southwestern Western Australia was largely cleared for wheat production, subsequently leading to its designation as a Global Biodiversity Hotspot given its high number of endemic plant species and rapid clearing rates. Since the 1970s, the greatest rates of forest clearance have been in southeastern Queensland and northern New South Wales, although Victoria is the most cleared state. Today, degradation is occurring in the largely forested tropical north due to rapidly expanding invasive weed species and altered fire regimes. Without clear policies to regenerate degraded forests and protect existing tracts at a massive scale, Australia stands to lose a large proportion of its remaining endemic biodiversity. The most important implications of the degree to which Australian forests have disappeared or been degraded are that management must emphasize the maintenance of existing primary forest patches, as well as focus on the regeneration of matrix areas between fragments to increase native habitat area, connectivity and ecosystem functions.

Keywords: biodiversity • climate change • fragmentation • land use • restoration

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Land clearance in Australia, as elsewhere in the world, is driven by the inexorably increasing human population and demand for socio-economic development.

Braithwaite (1996)

INTRODUCTION

Australia is the world's sixth largest country and the only one to occupy an entire continental mass. Populated by a relatively small number of human inhabitants (22.5 million), it is also one of the most developed countries. Despite its harsh climates, poor soil fertility and relative lack of water (Australia is the driest permanently inhabited continent on Earth), its economic and social successes suggest that its environmental policies have, at least in the most recent past, prevented large-scale environmental disasters that impinge on human well-being and prosperity. However, Australia has undergone massive land-use changes since human settlement, including transformation of the biota and forest structure by Aborigines going back as much as 75 000 years ago (Flannery 1998; Rasmussen *et al.* 2011). While generally adequate information exists on the state of Australia's environmental performance, it is available only in piecemeal literature, including popular books, region-specific and thematically

narrow scientific papers and government reports and databases.

As such, there is no single resource which overviews two particularly important aspects of land-use change and their consequences for biodiversity—deforestation and forest degradation. Indeed, worldwide as in Australia, habitat loss via vegetation clearing, mostly for agricultural expansion, is considered the most important driver of population decline and species extinctions (Bradshaw *et al.* 2009; Brook *et al.* 2008; Gibbs *et al.* 2010; Travis 2003). This lack of synthesis is particularly surprising given the technological advances in ecological monitoring over the last 30 years, and the fact that Australia's old growth eucalypt forests are biologically and evolutionarily unique; they have a relatively long evolutionary history compared with temperate and tropical forests elsewhere, because Australia as a continent has not undergone extensive glaciation (Norton 1996).

In this paper, I will address this gap by providing a concise overview of the trends in Australian deforestation and forest degradation since European colonization, but with a particular focus on the last 100 years. The patterns of pre-European deforestation and forest structure change as implemented through Aboriginal 'firestick' farming (Bliege Bird *et al.* 2008) is beyond the scope of the review; yet, the reader should keep in mind that Australian forests were far from 'pristine' (i.e. unaltered by humans) when the first Europeans settled eastern Australia in the late 18th century (Bliege Bird *et al.* 2008; Flannery 1998). My paper includes sections on the historical trends in deforestation, state-specific patterns of vegetation clearance, how plantations of exotic tree species have changed over time, the biodiversity implications of forest loss and degradation, climate change arising from deforestation, and finally a brief overview of the forest reserve system in Australia and the necessity for broadscale forest restoration. My overarching aim is to provide a relatively succinct, yet up-to-date, overview of the patterns of forest change in Australia and their implications for the country's biota. I conclude with several conservation management suggestions arising from the overview.

MODERN HISTORY OF LAND CLEARING

Notwithstanding the extensive changes to forest composition and cover by Aborigines prior to European contact through their manipulation of broadscale fire patterns (Bliege Bird *et al.* 2008), it has been estimated that ~30% of Australia's land mass was covered by 'forest' at the time of first European colonization in the late 18th century (Barson *et al.* 2000) (Fig. 1). Here, forest is defined as 'an area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height >2 m and with existing or potential crown cover of overstorey strata ⩾20%' (Australian Bureau of Rural Sciences 2010; Barson *et al.* 2000). At the same time, the majority (~40%) of Australia was covered with 'shrubland' habitat types typical of its mostly arid and desert interior. Open woodlands (i.e. with crown cover <20%) made up the next most

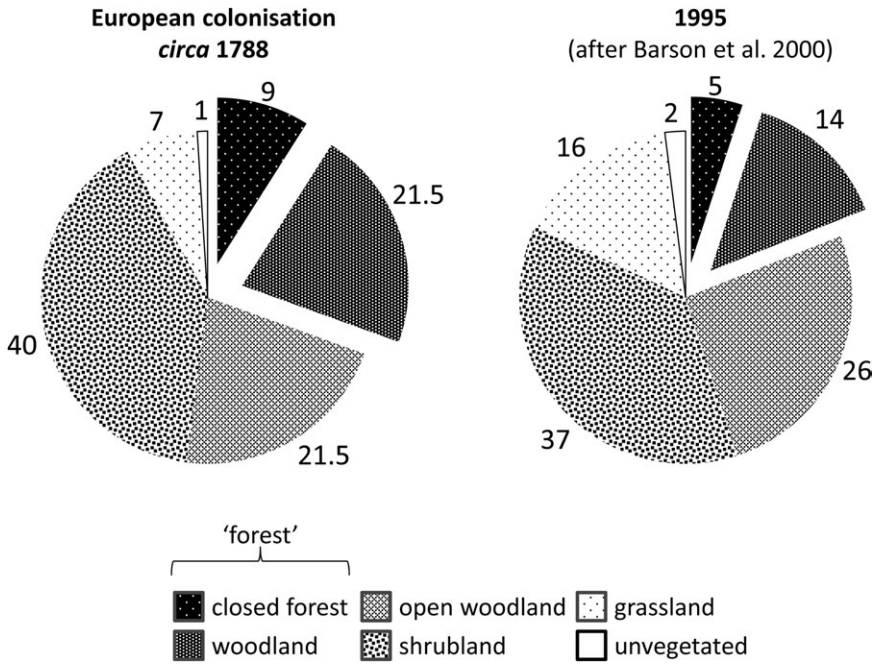

Figure 1: proportion change in major vegetation types in Australia from European colonization ~200 years ago until 1995 (data from Barson *et al.* 2000). 'Forest' (defined as 'an area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height >2 m and with existing or potential crown cover of overstorey strata ⩾20%') (Barson *et al.* 2000) includes both 'closed forest' and 'woodland' categories.

common general habitat type at around 22%, followed by grasslands (7%) and unvegetated areas (1%) (Barson *et al.* 2000) (Fig. 1).

After the first permanent European settlement was established in Sydney Cove in 1788, vegetation clearing for agriculture followed almost immediately. For this reason, the highest clearance rates were in those areas with soils best suited to agriculture (Braithwaite 1996) and generally in coastal areas. In 1861, the newly formed government of Australia passed the Crown Lands Alienation Act, which was designed to 'open up' the colony to settlement. Over the following century, that single Act effectively guaranteed the rapid clearing of vegetation by unrestricted settlement, for it penalized entitled landholders, via a forfeit to the Crown, for failing to 'develop' their lands (Braithwaite 1996). Thus, most land clearing occurred in southeastern Australia from the turn of the 19th century to the mid-20th century. In New South Wales, e.g. most deforestation occurred between 1892 and 1921, mainly from the rapid proliferation of the wheat and sheep industries (Norton 1996). Afterwards, emphasis shifted to southwestern Western Australia which experienced its most rapid deforestation between 1920 and the 1980s and to Queensland in more recent decades (Deo 2011). Indeed, most (>80%) of the 1.2 million ha cleared in Australia between 1991 and 1995 was in Queensland (Barson *et al.* 2000; Wilson *et al.* 2002). Although since the mid-1940s, forest clearing has been less extensive than what had occurred during the 19th century (Braithwaite 1996).

By the 1980s, ~38% of Australia's forests had been severely modified by clearing (Wells *et al.* 1984), and by 1995, Australia had the lowest total area of remaining closed forests (4.6% of her land mass) relative to 15 countries investigated (Singh *et al.* 2001; Fig. 2). Indeed, Australia has only ~4% of the world's forests on ~5% of the world's total land area (Australian Bureau of Rural Sciences 2010). Today, ~15% of the continent is now considered to have been severely modified by intensive land use, with agricultural areas dominated by cattle grazing zones covering around 43% of the country and 'improved' pastures covering around 10% (Deo 2011). In 1995, Graetz *et al.* (1995) estimated using satellite imagery that >1 000 000 km^2 (52%) of the country's intensive land-use zones had been cleared or modified. According to Commonwealth data to 2009 (Australian Bureau of Rural Sciences 2010), Australia's native forests now cover 147.4 million ha (1.474 million km^2) or now only 19% of her total land area—this represents a total loss of ~38% since European settlement. From a dominant-species/forest-type perspective, this means that the greatest losses continent wide have occurred in eucalypt forests (Fig. 3), which make up ~78% of the remaining forest vegetation (Australian Bureau of Rural Sciences 2010).

Yet, these figures neglect the fact that much of the remaining forest is now severely degraded. In total, ~50% of Australia's forest has now been completely cleared or severely modified, with over 80% of eucalypt forests in particular having been altered by human endeavour (Resource Assessment Commission 1992). Even those eucalypt forests are now under some type of protection, over 50% of those having been logged at some point in the past 200 years (Norton 1996). In north Queensland, e.g. around 28% of its inland dry rainforest patches have been cleared (Fensham 1996). Furthermore, much of the remaining forest cover is severely fragmented into small patches, especially in southeastern Australia, with roads, urban development, agriculture and plantations isolating existing fragments to the point that much of their biodiversity potential is severely compromised (Gill and Williams 1996).

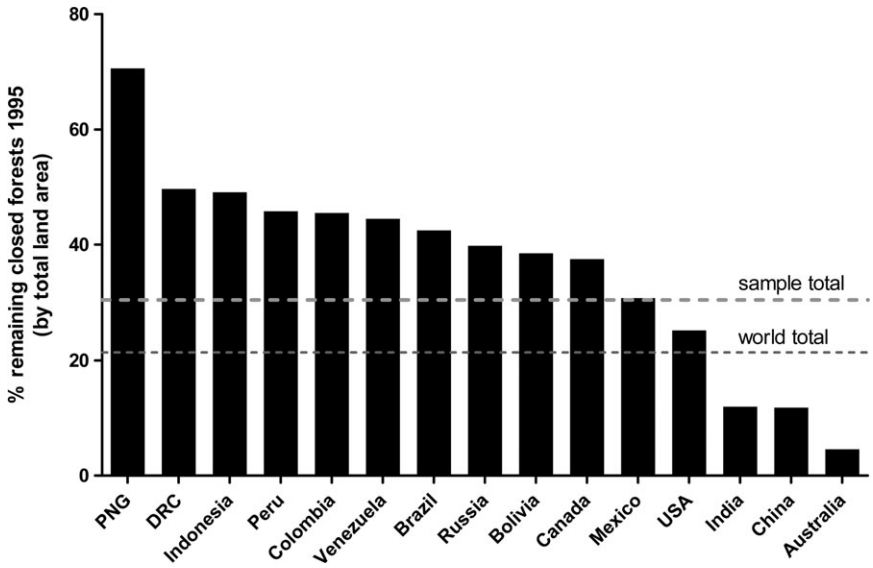

Figure 2: percentage of remaining closed forest by country for 15 countries sampled in 1995 (data from Singh *et al.* 2001). Australia has the lowest remaining closed forest as a percentage of total land area (4.6%) and is much lower than the sample (30.4%) and world (21.4%) totals. DRC = Democratic Republic of Congo; PNG = Papua New Guinea.

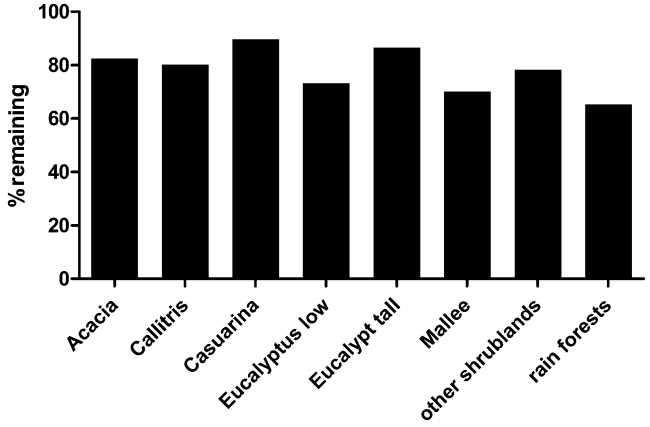

Figure 3: percentage of remaining forests by major dominant species or forest type (data from Australian Bureau of Rural Sciences 2010). Note that most (78%) forests in Australia are classified as either tall or low eucalypt forests.

NEW SOUTH WALES

Being one of the first regions settled by Europeans and having generally a higher human population than most other parts of the country, much of the removal and damage to New South Wales' forest ecosystems happened during the 19th century. As mentioned, the most expansive and rapid initial damage occurred on the most fertile soils where agriculture was most favoured, with the less-productive ecosystems within the sandstone and poorest soil areas being left largely intact (Braithwaite 1996). However, deforestation continued well into the next century and targeted specific ecosystems. For example, between 50 and 67% of the coolibah–black box (*Eucalyptus coolabah* and *Eucalyptus largiflorens*) woodland in northern New South Wales have been cleared since colonization, with an average of 135 km^2 removed each year between 1998 and 2004 (Keith *et al.* 2009a). In the Sydney region, <1% of the Sydney blue gum (*Eucalyptus saligna*) forests persist (Braithwaite 1996). Between 1972 and 1980, 430 000 ha $year^{-1}$ were cleared around the state (Reed 1990), with rates subsequently (post-1986) varying between 20 000 and 80 000 ha $year^{-1}$ within the eastern/central and western regions, respectively (Norton 1996). In the state's wheatbelt, around 70% of native woody vegetation was cleared between 1977 and 1985 (Sivertsen 1994). Even as late as the period from 1995 to 2005, New South Wales had the second highest average proportional land-clearance rates among Australia's states and territories (Fig. 4), and as of 2009, it is estimated that the state had a total remaining 26 208 000 ha of native forest or ~33% of its total area (Fig. 5).

SOUTH AUSTRALIA

South Australia's forests were also mostly cleared during the 19th and early 20th centuries (Szabo *et al.* 2011), where in some regions such as the Mount Lofty Ranges close to the state's

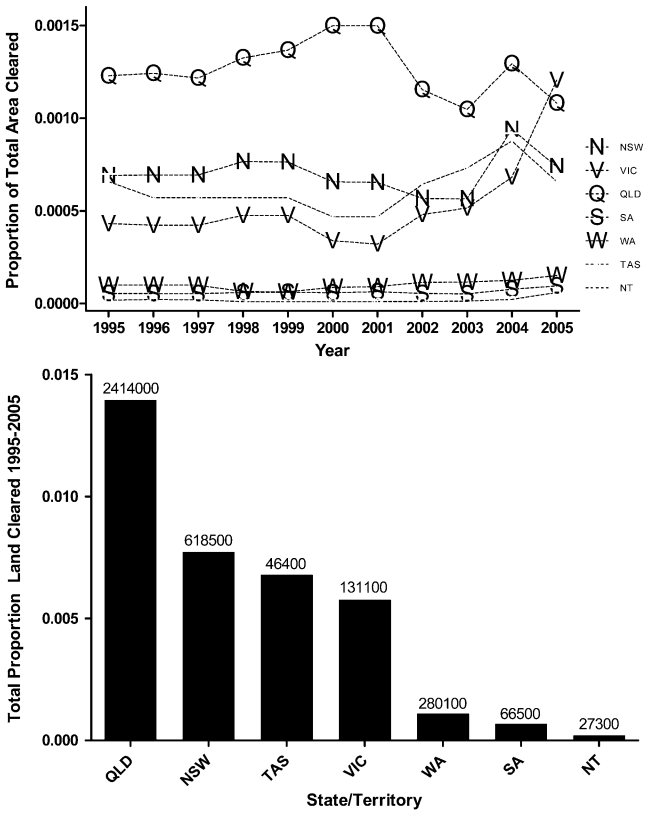

Figure 4: top panel: proportional forest clearance rates by state and year from 1995 to 2005 relative to total land area (data from Australian Bureau of Statistics 2009). Bottom panel: total proportional land clearance by state from 1995 to 2005 (Australian Bureau of Statistics 2009). Numbers above bars indicate total clearance in hectares.

primary urban centre (Adelaide) only 10% of woodlands remained when broadscale clearing largely ceased in 1980 (Paton and O'Connor 2009). But it was not until 1991 that the Native Vegetation Act of South Australia was passed, effectively banning any new vegetation clearance across the state. In the Adelaide plains region surrounding the Mounty Lofty Ranges, the situation is even worse, with only 4% of the original natural vegetation remaining (Oke 1997; Tait *et al.* 2005). Native forests are now estimated to cover only 9% of the state's total area (Australian Bureau of Rural Sciences 2010; Fig. 5).

WESTERN AUSTRALIA

Separated from the rest of Australia by harsh deserts and arid lands, the biota of Western Australia has evolved over 4 000 endemic plant and 100 vertebrate species (Myers *et al.* 2000). So unique is its biodiversity that the southwest of the state is now Australia's only Biodiversity Hotspot (www.biodiversityhotspots.org), a dubious distinction because it signifies global areas of high endemicity with exceptional loss of habitat (Myers *et al.* 2000). Indeed, as of 2000, ~90% of the Hotspot's 310 000-km^2 area of primary vegetation had been cleared (Myers *et al.* 2000). The reasons underlying this rapid and

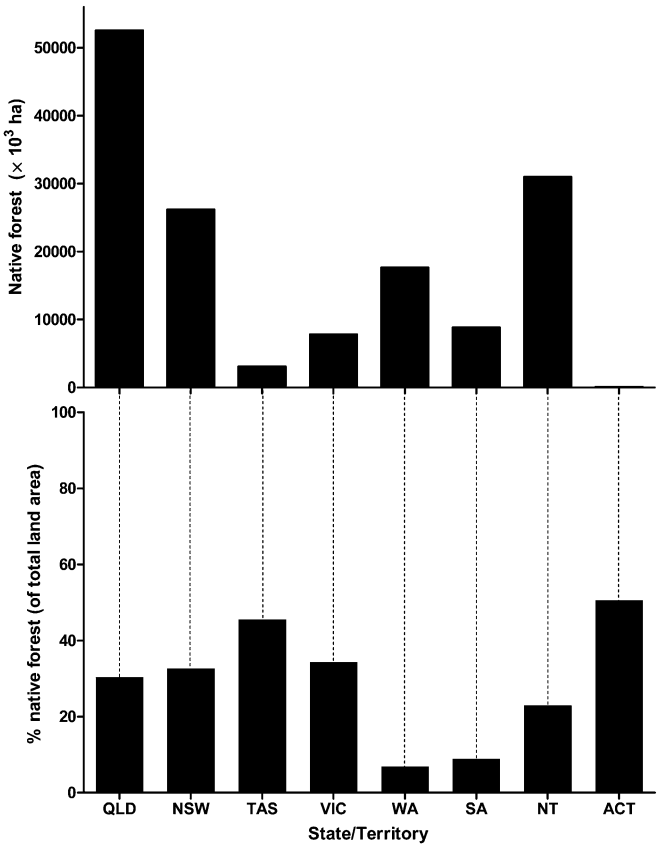

Figure 5: total native forest coverage by state expressed as an area (top panel) and as a percentage of total land area (bottom panel) (data from Australian Bureau of Rural Sciences 2010).

expansive loss are similar to elsewhere in Australia, but they are all the more tragic because it happened mainly in the mid-20th century; indeed, 54% of all land developed for agriculture was cleared from 1945 to 1982 (Saunders 1989). As of 2009, Western Australia had 17 664 000 ha of native vegetation, covering ~7% of its total land surface (Fig. 5).

But forest clearing began much earlier in Western Australia. During the 1890s, broadscale vegetation removal was done for the expansion of the sheep and wheat industries, continuing into the 20th century and gaining momentum after the Second World War (Allison and Hobbs 2006). The 140 000-km^2 area of southwest Western Australia that contains the Biodiversity Hotspot and now known as the 'wheatbelt' consisted mainly of a complex mosaic of salmon (*E. salmonophloia*), York (*Eucalyptus loxophleba*) and wandoo (*Eucalyptus wandoo*) woodlands, heath thickets and scrub (Saunders 1989). But by 1968, over 130 000 km^2 of that area had been cleared (Saunders 1989). And the clearing continued well into the late 1980s—the state government approved applications to clear between 30 000 and 60 000 ha year^{-1} during that decade (Schur 1990). In some parts, the devastation is near total. For example, in the central part of the wheatbelt (the Avon Botanical District), over 93% of the original vegetation was cleared, with up to 97% of woodlands removed (Saunders 1989). In another 1 680-km^2 area near Kellerberrin, 93% of the vegetation had been removed since 1940 (Saunders *et al.* 1993).

QUEENSLAND

Queensland's history of vegetation clearance is remarkable in that most of it occurred in the last 50 years (Accad *et al.* 2006; McAlpine *et al.* 2009), largely due to the expansion of the cattle industry (McAlpine *et al.* 2009), with the enforcement of clearing restrictions only coming into effect in the mid-2000s (Henry *et al.* 2005). Indeed, from the period of 1981–2000, Queensland was dubbed a global 'deforestation hotspot' (Lepers *et al.* 2005)—of the 1.2 million ha of woody vegetation cleared between 1991 and 1995 Australia wide, over 80% occurred in Queensland (Barson *et al.* 2000), and from 1995 to 2005 Queensland had the highest proportional clearance rates of any state or territory (Fig. 4). Prior to European settlement, ~80% of Queensland's land surface was covered with forests, shrublands and heathlands, with most occurring in the east and north (Wilson *et al.* 2002). Despite the recent legacy of rapid vegetation clearing, Queensland still has the greatest extent of native forests (52 582 000 km^2), although they now only represent ~30% of the state's land surface (Australian Bureau of Rural Sciences 2010; Fig. 5).

Historically, most of Queensland's forest clearance occurred within the south central and southeast, particularly in the fertile Brigalow Bioregion where most was removed in the 1960s (Lucas *et al.* 2008). However, even as late as 1999, the annual rate of deforestation in Queensland was 4 460 km^2, of which >60% was in the Brigalow (Johnson *et al.* 2000; Wilson *et al.* 2002). Today, the areas with the most fertile soils now have <10% native vegetation cover, and most of this is highly fragmented, often occurring as linear remnants within a pasture matrix (McAlpine *et al.* 2002, 2009; Wilson *et al.* 2002). In the heavily populated Brisbane region, 22% of the remaining native vegetation was cleared between 1982 and 1990 (Catterall and Kingston 1993) and 34% was cleared from the coastal southeast mainland between 1974 and 1989 (Sinclair *et al.* 1993).

In the tropical regions of Queensland, it is estimated that ~50% of its primary tropical forest (6 700 km^2 of around 13 000 km^2 originally) has been destroyed since European colonization (Myers 1988; Woinarski 2010), much of it for sugarcane, banana and livestock production (Rasiah *et al.* 2004). About 52% of the northeast wet tropics region is now under pasture (Productive Commission 2003). In the inland dry rainforest patches of north Queensland (between 17° and 23.4°S latitude), ~28% has been cleared, with the remainder confined largely to small, isolated fragments (Fensham 1996).

VICTORIA

According to the Victorian Government, ~66% of the state's native vegetation has been cleared since European colonization

(Victoria Department of Sustainability and Environment 2011), leaving 34% of the state's land area covered by native forests (7 837 000 ha; Fig. 5) (Australian Bureau of Rural Sciences 2010). According to Lindenmayer (2007), this makes Victoria the most heavily cleared state in the country. Most of the clearance occurred prior to the 1890s as the wheat and livestock industries expanded with European colonization; thereafter, clearance continued at a relatively stable rate of ~1% per year until 1987 when stringent anti-clearing legislation was introduced (Lindenmayer 2007). However, even from 1995 to 2005, proportional clearance rates remained high and even increased in the latter part of that decade to become the highest among all states and territories in 2005 (Fig. 4).

TASMANIA

Of the states and territories (Australian Capital Territory excluded), Tasmania has the highest proportion of remaining forest in the country (46%), which represents ~3 116 000 km^2 in total area (Australian Bureau of Rural Sciences 2010; Fig. 5). Forest loss began early in Tasmania but was largely restricted to the eastern region where sheep production was most intense. Between 1803 and 1964, this region's forest cover was reduced by ~60% (from 48 600 to 28 400 km^2) (Davies 1965). Statewide, the long-term average rate of deforestation was 11 000 ha $year^{-1}$ (Norton 1996), but this rate was much higher—17 000 ha $year^{-1}$—between 1972 and 1980 (Kirkpatrick 1991; Kirkpatrick and Dickinson 1982). Between 1980 and 1988, ~6 000 ha were cleared each year (Kirkpatrick 1991).

NORTHERN TERRITORY

In terms of deforestation, the Northern Territory has experienced the least amount of vegetation clearing of any state or territory (Fig. 4) (Woinarski *et al.* 2007), although its savannas and closed forests are far from pristine. Remoteness, a small human population, poor soils and an extreme monsoon have restricted agricultural development throughout most of the region. Indeed, the world's largest expanse of tropical savanna woodland is in northern Australia, with most of that in the Northern Territory (Woinarski *et al.* 2007). Today, the Northern Territory has ~23% (17 664 000 ha) of its land area covered by native forests (Fig. 5), and most of these are relatively intact at least in terms of canopy cover (Woinarski *et al.* 2007). However, markedly altered fire regimes, the proliferation of invasive plant and animal species and some pastoralism have been proffered as the main determinants of recent and catastrophic small mammal declines in the region (Woinarski *et al.* 2011).

PLANTATIONS

The establishment of exotic tree species in plantations for timber and fibre supply has a long history in Australia. Beginning in the 1870s, plantations comprised mainly of Monterey pine (*Pinus radiata*) increased in area to cover ~200 000 ha by the 1960s. From then to the 1990s, the area increased rapidly to cover over 1 000 000 ha, after which the emphasis shifted from pine to hardwood and eucalypt plantations (Australian Bureau of Statistics 2001; Barson *et al.* 2000). By 2009, the total area reported under plantation in Australia was 2 000 000 ha, with Victoria and Western Australia having the largest areas, of which roughly half consisted of hardwood species (Australian Bureau of Rural Sciences 2010). Recent work suggests that Australia's wood production surpasses its domestic wood consumption, and more importantly, the country's wood production derived from plantations outpaces that derived from native forests (Fig. 6), supplying some 80% of the wood-processing industry's raw material (Ajani 2008). This means that Australian processors should be able to meet most of their requirements without relying on native forest harvest (Ajani 2008); however, increasing plantation cover at the expense of any native vegetation will continue to cause biodiversity to decline (e.g. Lindenmayer *et al.* 2000), although there is certainly some biodiversity value improvements as plantations age and join previously disjunct native forest patches (Lindenmayer *et al.* 2008).

FOREST DEGRADATION AND BIODIVERSITY LOSS

It is worrisome in its own right that Australia has been subjected to such broadscale deforestation when, in global terms, the country had little forest cover to begin with. What is perhaps more distressing is that much of the remaining vegetation is highly fragmented, disturbed or ecologically compromised (Gill and Williams 1996), to the point where many plant and animal species have already gone extinct or are in immediate danger of extinction (Lindenmayer 2007; Norton 1996). Indeed, even by 1992, it was estimated that over 80% of eucalypt forests in Australia had been modified by humans in some way, and around

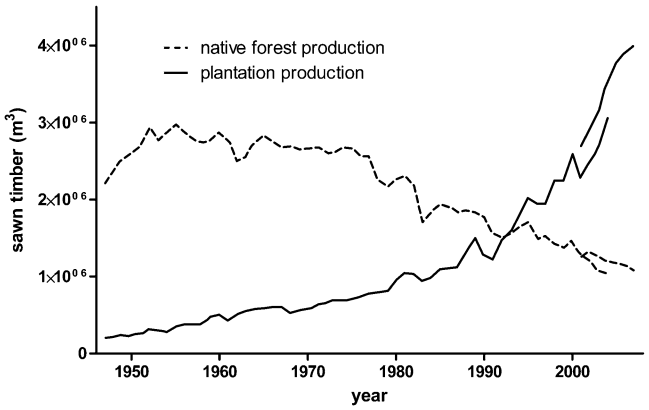

Figure 6: supply of sawn timber wood production by source (plantation or native forest) by year from 1947 to 2007 (Ajani 2008). The break at 2002 and overlapping trajectories indicate a change in methods to calculate total contributions from each source (Ajani 2008).

50% of such forests under any form of protection have been logged at some point since European colonization (Norton 1996; Resource Assessment Commission 1992). As such, statistics regarding total forest coverage (Fig. 5) provided by the Commonwealth Government (Australian Bureau of Rural Sciences 2010) are potentially misleading because they ignore the state of existing forests relative to their pre-European condition.

Fragmentation is the main modifier of forest ecosystem function and resilience, with relative intactness deteriorating as patches of remnant forest become smaller and more isolated (Saunders *et al.* 1991; Wilcox and Murphy 1985). There has been a substantial litany of studies in Australia assessing the effect of fragmentation on tropical (e.g. Goosem and Marsh 1997; Hannah *et al.* 2007; Laurance 1991; 1997) and temperate forests (e.g. Antos and White 2004; Davies *et al.* 2001; Debuse *et al.* 2007; Ford *et al.* 2009; Hester and Hobbs 1992; Hobbs 1993; Holland and Bennett 2010; Margules *et al.* 1994; Ross *et al.* 2002; Saunders *et al.* 1987; Yates *et al.* 1994), with all finding considerable detriment to biodiversity. Indeed, the time since fragmentation is an important consideration given that extinction lags (the time taken for all extinctions to occur following perturbation) can be on the order of decades or more (Ross *et al.* 2002). Examples of increasing fragmentation abound. In the Lockyer Valley catchment of Queensland, there was a 37% increase in the number of forest fragments between 1973 and 1997 and a 54% decrease in mean patch size (from 33.7 to 15.4 ha) (Apan *et al.* 2000). In the Herbert catchment (Queensland), mean eucalypt woodland patch size decreased from 818 ha in 1860, 546 ha in 1943, 465 ha in 1977 and to 392 ha in 1996 (Johnson *et al.* 2000). In the Kellerberrin region of Western Australia's wheatbelt, the 93% vegetation removal since 1940 has resulted in patches that are mostly (77%) <20 ha in size (Saunders *et al.* 1993). Another example is in the Mount Lofty Ranges of South Australia where only 10% of the original vegetation exists in remnants that are highly patchy and largely unrepresentative of historical conditions (Westphal *et al.* 2003). For example, the region had ~4 000 separate patches of native vegetation in the late 1990s, with a mean size of only 13.1 ha (standard deviation = 26.5 ha) (Westphal *et al.* 2003). This is considered to be approximately two orders of magnitude smaller than what is required to maintain a healthy bird biota (Westphal *et al.* 2003).

On a global scale, the biodiversity in temperate eucalypt forests is still relatively high (Norton 1996), although certain regions and taxa have suffered greatly as a result of forest loss and degradation. Even in areas that have largely escaped the deforestation wave, extensive grazing within has had large, negative effects on the biodiversity of Australia's tropical savannas, particularly for small mammals (Crowley and Garnett 1998; McAlpine *et al.* 2009; Sharp and Whittaker 2003; Woinarski *et al.* 2007, 2010, 2011). But most research in this domain has focussed on forest birds (Ford 2011). For example, many bird species have been lost from or are in severe population decline in the Mount Lofty Ranges in South Australia (Szabo *et al.* 2011), Victoria (Bennett 1993; Loyn 1987; Traill *et al.* 1996), New South Wales (Barrett *et al.* 1994; Ford 2011), Queensland (Hannah *et al.* 2007; Woinarski and Catterall 2004; Woinarski *et al.* 2006) and the wheatbelt of Western Australia (Saunders 1989). Other taxa have been examined, but to a lesser extent. For example, in the highly fragmented Brigalow region of Queensland, reptiles have declined considerably (Covacevich *et al.* 1998); elsewhere (Australian Capital Territory), reptiles have shifted elevational limits in response to temperature increases arising from fine-scale fragmentation (Shine *et al.* 2002). There is also substantial evidence for declines in floristic diversity, exacerbated by invasion of exotic grass species from adjacent pastures (Fairfax and Fensham 2000; McAlpine *et al.* 2009), as well as mammal declines in relation to fragmentation (Lindenmayer *et al.* 2000).

In the Mount Lofty Ranges of South Australia in particular, biodiversity losses have been severe. At least 132 species of animals (including 50% of the mammal fauna) and plants have become locally extinct, and at least 648 non-indigenous species (mostly plants) have been introduced (Tait *et al.* 2005). Szabo *et al.* (2011) even suggested that the catastrophic losses there should designate the region as a 'canary' landscape for temperate woodlands around Australia, given the lag times in extinctions generally seen following forest disturbance. Indeed, Recher and Lim (1990) noted that across Australia, local extinctions of animal vertebrates generally occur within decades, and perhaps longer (McAlpine *et al.* 2009), of deforestation arising from agriculture. Forest remnants resurveyed 20 years after initial clearing had an average loss of 8.8 bird species (MacHunter *et al.* 2006), and similar progressive losses of birds have been observed in the northern tablelands of New South Wales over 30 years (Ford 2011).

CLIMATE CHANGE

Deforestation has two principal effects on climate. First, the physical act of vegetation clearance releases substantial quantities of greenhouse gases into the atmosphere, which increases overall carbon emissions and exacerbates anthropogenic climate change (IPCC 2007). In 1980, the clearing of vegetation released an estimated 28 million tonnes of carbon, and land-use change (mainly from vegetation clearance) contributed 22% to Australia's greenhouse gas emissions in 1990 (Australian Greenhouse Office 2005), although this amount has declined in recent decades with the implementation of anti-clearing legislation (Kirschbaum *et al.* 2008). A study of the carbon-carrying capacity of 14.5 million ha of native eucalypt forests in Queensland, New South Wales, Victoria and Tasmania indicated a capacity of 640 tonnes C ha^{-1}, or 33 billion tonnes of CO_2 equivalents in the forests' natural state (Mackey *et al.* 2008). Given that over half of the area has been cleared or heavily modified, the potential for increasing carbon sequestration via restoration is massive (Ajani 2008). Indeed, the world's highest total biomass carbon density (both living and dead tissue—1 867 tonnes C ha^{-1}) is found in the moist temperate *Eucalyptus regnans* eucalypt forests of Victoria (Keith *et al.* 2009b).

Australia has warmed over the last century by an average of ~1.0°C, with the most rapid and pronounced warming occurring in eastern Australia since the 1950s (Nicholls 2006). There has been a concomitant increase in the frequency of hot days and nights and a decline in cold days and nights (Deo 2011). Australia has also experienced rapid shifts in rainfall patterns over this period, with decreased rainfall in the southeastern and southwestern regions and increases in the northwest (Nicholls and Lavery 1992). In eastern Australia, there is also evidence that periods of drought are becoming hotter since 1973 (Nicholls 2004).

Forest clearance over large areas also affects local climate conditions such as temperature variation and precipitation patterns (Deo 2011; Deo *et al.* 2009; Junkermann *et al.* 2009; Narisma and Pitman 2003, 2006; Pitman *et al.* 2004). As a result of modifying vegetation cover, the solar energy available for plant transpiration, evaporation and convection between the land and the atmosphere and soil moisture feedbacks are all changed, leading to more rapid local climate anomalies (Deo 2011). Many of these changes are driven by the complex interaction between emissions, global climate and local land-use change. Examining temperature and rainfall patterns in relation to land cover modification, Deo *et al.* (2009) showed that vegetation clearance had added to temperature increases and reductions in rainfall, especially during strong El Niño years, such that droughts lasted longer and were more extreme (i.e. hotter and drier) compared to areas with more vegetation cover. Similar conclusions have been drawn for Queensland (McAlpine *et al.* 2007) and for Australia's tropical savannas via simulation modelling (Hoffmann *et al.* 2002). In Western Australia, there was a rapid decline in rainfall during the 1950–960s, part of which was attributable to forest clearance that peaked during that time (Narisma and Pitman 2003; Pitman *et al.* 2004). Much of this can be explained by the reduced surface roughness following clearance by changing moisture divergence regionally and by increasing wind magnitudes (Pitman *et al.* 2004).

PROTECTION

Although there was little planning involved initially, Australia (like many other countries) started to take preservation of natural ecosystems seriously in the mid-1990s, such that now Australia has ~11% of its 7.7 million-km^2 land area within the National Reserve System (Watson *et al.* 2009). According to Commonwealth statistics, this means that around 16% of native forests in Australia are now under some form of protection (i.e. 23 of 147.4 million ha) (Australian Bureau of Rural Sciences 2010). Using estimates of the total wilderness area (i.e. large areas that have experienced minimal habitat loss) in Australia Watson *et al.* (2009) determined that of the 2.93 million km^2 of wilderness (38% of land area, mostly in northern and western Australia), only 14% was protected in 2000. This value increased marginally to 19% by 2006 as the size of the Reserve System itself increased by 37% (i.e. from 652 597 to 895 326 km^2). The proportion of forests in Australia now falling within nature conservation reserves has increased from 11 to 16% from 1998 to 2008 (Australian Bureau of Rural Sciences 2010). In other words, the growth in reserve area did not capture the necessary wilderness; instead, gains were made in areas largely modified by humans. Even where wilderness (including intact native forests) has been captured, it is predominately within areas incorporating mining, forestry and livestock grazing, e.g. Indeed, Wilson *et al.* (2002) determined that between 50 and 91% of ecosystems that had experienced extensive clearing in the past are now protected.

The situation in the tropics is encouraging—most tropical forests in Australia are now protected in some form, and so there is no longer any extensive clearing in these regions (Woinarski 2010). However, the legacy of deforestation and fragmentation that occurred prior to protection means that many extinctions are likely to occur over the coming decades unless efforts to restore vast areas (especially in north Queensland) are implemented (Woinarski 2010).

CONSERVATION IMPLICATIONS

The patterns of deforestation and forest degradation in a country well-known for its relatively low forest cover globally indicate that major shifts in environmental policy are required. While state and national legislation to protect forests came into force throughout the 1990s and 2000s in most parts of Australia, the legacy of deforestation means that a business-as-usual attitude will be insufficient to prevent further extinctions. Recent evidence from the tropical realm demonstrates clearly that primary forests support, without exception, more diverse and structurally complex biotas than their degraded counterparts, even when degradation is mild (e.g. selectively logging) (Gibson *et al.* 2011). While an analogous study has yet to be applied to temperate forest ecosystems, the conclusion is likely to be upheld in these areas as well; indeed, we do know that plantations of exotic tree species have some, albeit substantially reduced, biodiversity value (Lindenmayer *et al.* 2008). As such, Australia's foundational forest conservation policy must be in the protection of existing tracts and fragments of primary forest.

In addition to this reinforcement of a protectionist policy, clearly, the most proactive means to enhance the value of remaining native forests for Australian biodiversity and to combat the ravages of deforestation on local climates is to implement broadscale reforestation projects around the country. Focussing on the most damaged ecosystems, such as the southwest of Western Australia, the forests of central and western Victoria, the Mounty Lofty Ranges of South Australia and Queensland's southern regions and wet tropics, is likely where we will observe our greatest gains. Fortunately, there has been an emphasis on protection throughout many of these regions over the past decade, such as the establishment of new reserves in South Australia and northern New South Wales, World Heritage Listing in the wet tropics, the increasing popularity of private agreements

between landholders and state governments for the gazetting of privately owned native vegetation remnants, private acquisition of large tracts of land by non-governmental organizations, replanting schemes funded via Commonwealth initiatives (Ford 2011), and biodiversity corridor plans for many areas on the southern, eastern and northern coasts of the country.

Such restoration will have multiple benefits, not least of which will be the maintenance of an increasingly threatened biota and the ecosystem services they provide (Hobbs 2009). Indeed, there are many studies showing that birds in particular respond well to forest restoration (reviewed in Ford 2011). Simulation and empirical climate studies also indicate a strong likelihood of increasing rainfall in drought-affected regions such as southwest Western Australia that are possible via broadscale reforestation (Pitman *et al.* 2004), as well as reducing expected increases in temperature by 2050 to as much as 40% (Narisma and Pitman 2006).

But restoration efforts must be planned carefully to provide the most cost-effective gains. A central conclusion of forest conservation ecology over the past 50 years is that fragment area is one of the main determinants of extinction risk for most taxa studied to date (reviewed in Sodhi *et al.* 2009). As fragments increase in size, the number of species they can support also increases and the negative effects of 'edge' dynamics (e.g. altered micro-climates and invasion of exotic species) dissipate (Haddad 2009). Thus, forest regeneration and enhancement projects should ideally focus on enlarging or joining existing primary forest fragments with a view to increase the overall area of contiguous native forest. Planting schemes will also require ecosystem-specific research to determine which planting protocols provide the best and most cost-effective long-term outcomes for local biodiversity and forest carbon sequestration potential. Restoration efforts will also require careful planning to maximize the landscape-scale representativeness of native species falling under protection for the lowest costs of land acquisition and lost economic opportunity (Turner and Pressey 2009).

Australia still has the luxury of returning much of its native ecosystems to more functionally resilient states given its relative prosperity and the momentum of change that has gripped the country in the last few decades. Obviously, a careful balance must be struck between agricultural production to supply food for a growing human population and biodiversity conservation, and this will be the biggest challenge over the coming decades.

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