

Ecosystem risk assessment of Georgina gidgee woodlands in central Australia

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Abstract Ecosystems across the world, and the biodiversity they support, are experiencing increasing anthropogenic pressure, and many will not persist without intervention. Given their complexity, the International Union for Conservation of Nature has adopted an international standard for ecosystem risk assessment that builds on the strengths of the species-based Red List criteria. We applied this protocol to the relatively understudied Georgina gidgee woodland ecosystem, which has a patchy but widespread distribution in central Australia. To address the extensive knowledge gaps, we gathered data to provide the first description of the characteristic biota, distribution of dominant species and the processes that support the ecosystem. Criteria evaluated include historical, current and future declines in spatial distribution, the extent and area of occupancy, and disruptions to abiotic and biotic processes. Future declines in suitable habitat were based on key climatic variables of rainfall, temperature and soil substrate. We also quantified the uncertainty in bioclimatic models and scenarios as part of predicting degradation of the abiotic environment. Overall, we assessed the risk status of Georgina gidgee woodlands as vulnerable based on the degradation of abiotic and biotic processes. Bioclimatically suitable habitat was predicted to decline by at least 30% in eight scenarios over the period 2000 to 2050. Predicted declines in overall suitable habitat varied substantially across all scenarios (7–95%). Pressures from grazing, weed encroachment and altered fire regimes further threaten the ecosystem; therefore, vulnerable status was also recorded for future declines based on altered biotic processes. Accurate mapping and monitoring of the study ecosystem should receive priority to inform conservation decisions, and sustainable grazing practices encouraged. Our findings focus attention on other patchily distributed ecosystems that may also have escaped attention despite their contribution to supporting unique biodiversity and ecosystem services. It is timely that environmental monitoring and policy account for these natural assets.

Key words: *Acacia*, desert, ecosystem risk assessment, IUCN Red List, woodland.

INTRODUCTION

To secure the future of biodiversity and ecosystem function, any risks of degradation must be established, and actions devised to reverse or slow resulting losses of ecosystem services that humans depend upon. In response to this need, the International Union for Conservation of Nature (IUCN) has adopted an international standard for risk assessment of ecosystems (Keith *et al.* 2013) based on the well-established IUCN Red List criteria for individual species. The key component of the assessment is a set of quantitative decision rules that address the distribution and function of the target ecosystems. Our primary aim here is to trial the relatively new protocols of Keith *et al.*

(2013) on an understudied woodland ecosystem in central Australia. In our case study, we also document current knowledge of biodiversity of the woodland and explore the additional challenge of determining risks for an ecosystem that has a naturally fragmented and patchy distribution.

Woodlands have been extensively cleared for agriculture or other development in Australia (Lindenmayer *et al.* 2014) and worldwide (Ramankutty & Foley 1999). Generally, such broad-scale trends are identified by direct observations, but vast remotely located ecosystems remain poorly known as they are less frequently visited. Alternatively, large areas can be assessed by remote sensing, but if woodland patches are smaller than the grid cells of remotely sensed datasets, for example, 250 m for the Moderate Resolution Imaging Spectroradiometer system (Levin *et al.* 2012), the information necessary to monitor changes

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will often be lacking. Despite being sparse and patchy, woodlands in arid regions can be important local 'hot spots' for biological activity, acting both as refugia for sedentary organisms and as stepping stones for more mobile ones (Free *et al.* 2013). Assessments of change for such ecosystems are consequently crucial but challenging to undertake, but see Fensham *et al.* (1998).

In central Australia, several species of *Acacia* grow as isolated individuals or in small patches scattered over large areas. Some, such as *Acacia peuce* and *Acacia pickardii*, receive conservation attention as threatened species (Nano *et al.* 2012; Raghu *et al.* 2013). Here, we focus on Georgina gidgee, or gidyea (*Acacia georginae* F M Bailey) woodlands and take an ecosystem approach, by including species across several trophic levels that depend on the existence of these tree-dominated habitats. These woodlands occur over large areas in the longitudinal dune fields and fringing areas of arid central Australia, but at the local scale are distributed patchily in clay swales between dunes (Purdie 1984; Dickman *et al.* 2011; Frank *et al.* 2014) or elsewhere on calcareous and alluvial soils (Beadle 1981). Typically, the patches are elliptical in shape and cover 0.5 ha to 10 ha (Fig. 1) but are omitted from broad-scale vegetation classifications and mapping. For instance, the geographical area encompassing the Georgina gidgee woodlands (Fig. 2) is designated as hummock grassland, dominated by hard spinifex (*Triodia basedowii*) (Dickman *et al.* 2014).

Naturally patchy ecosystems in remote areas present different conservation challenges compared to fragmented remnants of previously widespread woodlands. Hummock grassland has been little cleared (<2%; Smyth *et al.* 2012) and is considered widespread, perhaps explaining why scattered gidgee woodlands within that matrix have not previously been subject to conservation assessment. Yet, woody stems have been removed to fence thousands of kilometres of pastoral property in the rangelands (Wardle 2010). The ecosystem is impacted currently by firewood removal and by trampling, browsing and inputs of nutrients from livestock and feral camels (Frank *et al.* 2013, 2014). As mature trees are relatively long-lived (>200 years) and recruitment appears to be episodic, rather than annual or seasonal, recovery from adverse conditions is slow. Although there are no data on regeneration of *A. georginae*, recent studies on the more widespread but closely related *Acacia cambagei* show that seedling establishment occurs after a series of wet years and may lead to dense stands of young trees (Fensham & Fairfax 2005). Adult *A. cambagei* will generally survive fire, but fire affects recruitment in contrasting ways: juveniles in woody thickets are killed by fire, but in the absence of fire the natural self-thinning process that leads to mature trees, may take a century (Fensham & Fairfax 2005). Taken together, these observations indicate that Georgina gidgee woodlands represent an ecosystem that is

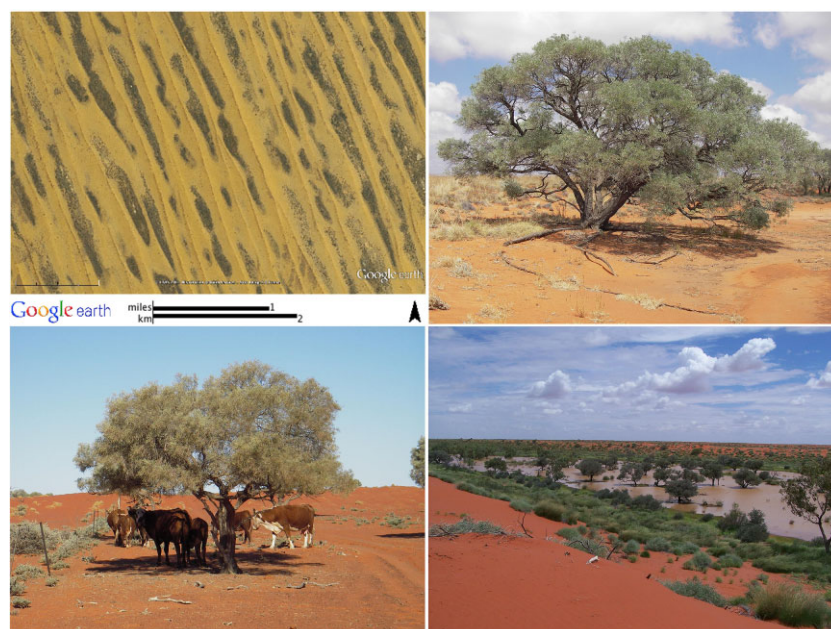


Fig. 1. Images of Georgina gidgee woodland. Top left: Patches of woodland showing linear to elliptical shape and interspersed distribution in the swales of the NNW/SSE longitudinal sand dunes of the Simpson Desert. The surrounding matrix is dominated by the hummock grass, *Triodia basedowii*, here the image showing reddish colour of the sand as the grass cover has been removed after widespread wildfires in 2011 and 2012. Top right: An adult gidgee tree at the edge of a clay pan. Bottom left: Cattle use gidgee trees for shade. This tree shows a browse line. Bottom right: Gidgee trees flooded after an extreme rainfall event.

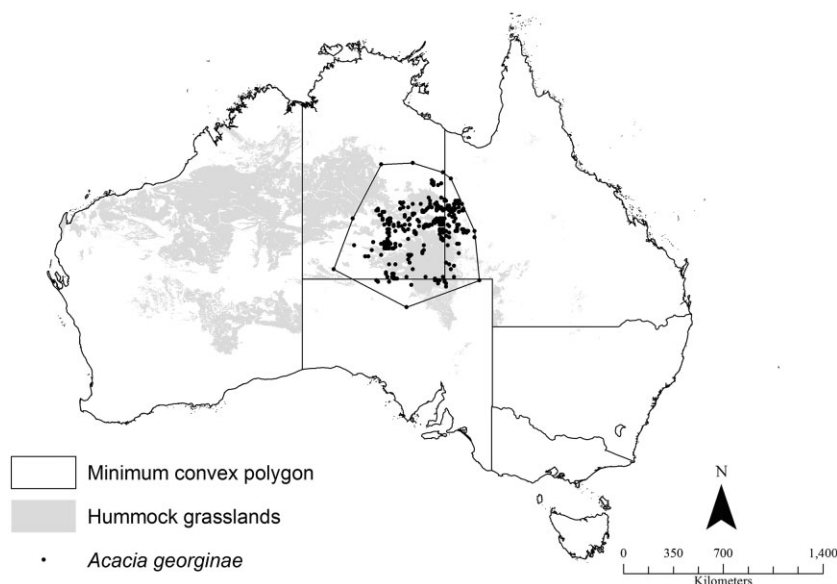


Fig. 2. Point locations where *Acacia georginae* is known to occur and minimum convex polygon enclosing known locations. Source: Atlas of Living Australia. The distribution of hummock grasslands is shown for comparison, as that is the major vegetation class describing areas where Georgina gidgee woodlands are found. Further details on the locations of *A. georginae* within 10×10 km grid cells are provided in Appendixes S8–S13.

potentially at risk from altered environmental conditions.

In this paper, we first describe the ecosystem, as this has not previously been done – emphasizing that our concept of the Georgina gidgee woodlands is of an entire ecosystem with flora, fauna and relevant abiotic components. Although *A. georginae* is the single dominant tree species in this ecosystem, it occurs with varying associated understory and ground plants, a soil microbial community and invertebrate and vertebrate fauna, some of which, such as birds or mammals, may be transiently present. Second, we provide a conceptual model to identify the key processes and interactions that drive the system, including any threatening processes to help determine what factors might constitute ecosystem collapse. Finally, we present the formal assessment of this ecosystem using a combination of available evidence, modelled projections and uncertainty estimates. Specifically, to address uncertainty in the projections used to evaluate the likely degradation of the abiotic environment, we ask two questions: (i) how do alternative climate models and scenarios based on varying human-driven and natural changes in greenhouse gases influence projected changes in suitable habitat; and, (ii) how does the inclusion of climate and/or soil variables influence the projected changes in suitable habitat? We expect that scenarios based on earlier interventions, and therefore earlier and smaller peaks in greenhouse gas emissions, will produce the least reduction in suitable habitat.

We base our conclusions on the combined evidence and make recommendations on where further efforts are needed to monitor this ecosystem, and other similarly patchily distributed ecosystems.

METHODS

Classification

The Georgina gidgee woodland ecosystem is typically overlooked or aggregated into other groups. The classic monograph on the vegetation of Australia by Beadle (1981) tentatively places Georgina gidgee woodlands as a distinct component of the *A. cambagei* alliance. Mirroring this perspective, Johnson and Burrows (1981) use the broad category of Acacia open forest and woodlands on deep fine-textured alkaline soils, but provide few details of the associated species.

Under the National Vegetation Information System (Anon 2006), *A. georginae*-dominated woodlands might be expected to fall into three major vegetation groups (MVGs), namely, MVG 6 Acacia forests and woodlands, MVG13 Acacia open woodlands and MVG 16 Acacia shrublands. However, based on mapped areas, the Georgina gidgee woodlands mostly are located geographically within the region designated as MVG 20 Hummock grasslands.

Four species within *Acacia* are commonly known as gidgee (*A. cambagei*, *A. calcicola*, *A. georginae* and *A. pruinocarpa*), but none has been classified internationally by IUCN or nationally under the Environment Protection and Biodiversity Conservation Act 1999. Georgina gidgee woodlands also

differ from other *Acacia*-dominated ecosystems such as acacia shrublands, acacia woodlands and acacia forests in their characteristic species (Foulkes *et al.* 2014).

Distribution and environment

Gidgee woodlands are strongly associated with arid to semi-arid climates in central Australia where summer rainfall is dominant and usually less than 350 mm a year, and often but not exclusively with clay soils. *Acacia georginae* occurs mostly in Queensland and in the Northern Territory, with a few records in northern South Australia. Mean annual daily maximum and minimum temperatures range from 27°C to 30°C and 12°C to 15°C, respectively (Australian Bureau of Meteorology 2014). However, during summer, daily temperatures usually exceed 40°C and minima in winter fall below 5°C (Dickman *et al.* 2010). Not surprisingly, Georgina gidgee woodlands fall within the hot deserts category: 8.1; under the IUCN (2014) Habitats Classification Scheme (Version 3.1).

Risk assessment

Formal assessment of this ecosystem in terms of critically endangered (CR), endangered (EN), vulnerable (VU) or least concern (LC) is made under five criteria: A, reduction in distribution; B, distribution size; C, environmental degradation; D, disruption of biotic processes or interactions; and E, a quantitative estimate of the risk of collapse. We adduce the evidence that is available for each criterion based on our review of threatening processes, and use this and modelled projections of the future distribution of this ecosystem.

To assess decline in distribution (criterion A), we examined changes in the known geographic distribution of *A. georginae* woodlands. Data from the State of the Environment 2011 Committee indicate little clearing of gidgee woodlands (Lindenmayer *et al.* 2014); however, accurate information at fine spatial scales is lacking. To illustrate the challenges of tracking changes in woodlands that have low percentage cover but which extend over vast areas of central Australia, we considered Landsat imagery on three properties in the northeastern Simpson Desert where the area of woodlands covers 269 km² (2.2%) of a total area of 12 319 km², with a further 305 km² (2.5%) representing clay pans.

The assessments of extent (B1), area (B2) and number of locations (B3) were based on a minimum convex polygon enclosing verified mapped occurrences of *A. georginae* in any of the 10 × 10 km cells. The ecosystem was deemed threatened if the area was less than 50 000 km², or if fewer than 50 cells were occupied.

As global climate change is a key environmental degradation factor for *A. georginae* woodlands, we suggest that variables suitable for assessing criterion C are extreme temperature and rainfall events (Greenville *et al.* 2012). Our reasoning rests on the assumption that persistence of Georgina gidgee woodlands is sensitive to the frequency and/or intensity of extreme rainfall events and/or prolonged droughts. Empirical evidence is limited, but based on 25 years of observations, it appears that suitable conditions for

recruitment are limited to extremely wet years, which occur only intermittently (decadal) and would be further limited by extreme temperatures. The available data on boom-bust responses to climatic fluctuations for the many other species that depend on gidgee woodlands (Dickman *et al.* 2014) confirm that an examination of the consequences of long-term trends in these events is warranted. To investigate the effects of climate change on habitat suitability of *A. georginae* woodlands, we used presence records extracted from the Atlas of Living Australia (Fig. 2) and bioclimatic variables derived from the WorldClim database (version 1.4; www.worldclim.org) (Hijmans *et al.* 2005). Presence records were checked for accuracy by cross-referencing with global positioning system coordinates, and outliers removed. To minimize collinearity, bioclimatic variables with correlation values less than 0.7 were retained (Elith *et al.* 2010; Dormann *et al.* 2013). Bioclimatic variables expected to be influential for arid and semi-arid biota (i.e. the variables best representing extremes of temperature and rainfall, Greenville *et al.* 2012) were used: mean diurnal range (bio2), maximum temperature of warmest month (bio5), minimum temperature of coldest month (bio6), precipitation of wettest month (bio13), precipitation of driest month (bio14) (Table 1).

Uncertainty in bioclimatic models was examined by running IPCC AR4 (A1B) and AR5 climate scenarios downloaded from the Climate Change, Agriculture and Food Security website (CCAFS; www.ccafs-climate.org). The A1B scenario predicts rapid economic growth, balanced use of fossil energies and peak global population around 2050. Data were derived from CSIRO Mk 3.0, a comprehensive global climate model with an improved atmosphere-ocean feedback system and no artificial corrections (Gordon *et al.* 2002). The AR5 projections were derived from the CSIRO Mk3.6 climate model that includes ocean, sea-ice and soil-canopy models, and is distinctive in including an interactive aerosol treatment and updated radiation pattern (Jeffrey *et al.* 2013). The four representative concentration pathway (RCP) scenario pathways measured in watts per square metre are labelled by the additional energy taken up by the Earth due to extra global annual greenhouse gas emissions for target levels in 2100; RCP 2.6 represents a low radiative forcing level and is expected to peak in 2010–2020 then decline, RCP 4.5 and 6.0 will stabilize at the medium target level without overshoot by 2100, and RCP 8.5 is a high level of forcing that will continue to rise throughout the 21st century (van Vuuren *et al.* 2011).

We also compared a 'conservative best-case scenario' model (climate only) with a 'restrictive, worst-case' model (climate-and-soil) by incorporating a categorical soil type layer and bioregion layer to the AR5 climate data. We predicted that the AR5 RCP 2.6 scenario, without the further restriction of suitable soil substrates, would lead to least change in habitat suitability for gidgee woodlands.

Spatial data for soil regions were downloaded from The Australian Soil Resource Information System (www.asris.csiro.au) using the classification from Isbell (2002). Bioregion data were downloaded from the Interim Biogeographic Regionalization for Australia (IBRA 7; Department of Environment 2012). The worst-case model was restricted to the IBRA and soil regions where occurrences of gidgee have been recorded (Appendix S1). Australia was classified by IBRA into 89 regions based on areas that have similar

Table 1. Variables used in the bioclimatic model for Georgina gidgee woodlands (*Acacia georginae*)

Variable	Description	Rationale
Mean diurnal range	The average of each month's maximum temperature minus its minimum.	Temperature related to growth and evaporation. Encompasses extreme temperature ranges.
Maximum temperature of warmest month (°C)	The highest temperature of any monthly maximum temperature.	Temperature related to growth and evaporation. Maximum temperature used as an estimate of changes in extreme heat.
Minimum temperature of coldest month (°C)	The lowest temperature of any monthly minimum temperature.	Temperature related to growth and evaporation. Minimum temperature used as an estimate of changes in extreme cold.
Precipitation of wettest month (mm)	The total sum of rainfall for the month that has the most rainfall in a given year.	Precipitation is the major input of moisture in central Australia. Wettest month chosen as an estimate of changes in extreme rain events.
Precipitation of driest month (mm)	The total sum of rainfall for the month that has the least rainfall in a given year.	Precipitation is the major input of moisture in central Australia. Driest month chosen as an estimate of changes in extreme dry periods.
Bioregion	Interim Biogeographic Regionalization for Australia (IBRA 7). Australia is divided into 89 different 'bioregions'.	Landscape factor based on common climate, geology, landform, native vegetation and species information. Contains data that may not be captured by other variables.
Soil type	The Australian Soil Atlas classification system as outlined by Isbell (2002). Classifies Australian soils into 14 broad groups.	Soil is an important, yet often neglected, environmental predictor for plant distributions. Gidgee is strongly associated with clay soils.

Bioclimatic variables were derived from WorldClim database version 1.4, unless otherwise stated.

climate, geology, topography and vegetation groups, and is therefore a useful limiting factor in habitat suitability predictions.

We projected the distribution of suitable habitats from 2000 to 2070 but report on outputs to 2050 (see below). All spatial data layers were clipped to Australia in ArcGIS 10.1 (ESRI 2012) using a 2.5 arc-minute (5 km² grid) resolution. Models were run in MaxEnt v3.3.3k (Phillips *et al.* 2006; Phillips & Dudik 2008) with 5000 iterations and 25 replications to permit model convergence. Model performance was judged using area under the receiver operating characteristic curve (AUC) values. The probability of habitat suitability (P(suitability)), based on five categories of suitability ranging from 0% to 100%, was calculated per time step as the percentage change in area from 2000. Total P(suitability) was also calculated from concatenating data from 20% to 100% P(suitability). To address the C2 criterion, we used the 50-year period between 2000 and 2050 to assess: (i) changes in the predicted area of all suitable habitat using total P(suitability) ($\geq 20\%$); and, (ii) changes in the predicted area of high-quality habitat using $\geq 60\%$ P(suitability).

There is no quantitative evidence that historic changes (C3) in climate have reduced *A. georginae* woodland areas since European settlement of Australia. The status of the ecosystem is therefore data deficient under criterion C3.

The main factor contributing to a disruption in biotic processes or interactions of *A. georginae* woodlands is grazing. Therefore, variables suitable for assessing criterion D are changes in species richness and reproductive output of native biota under different grazing pressures. To assess the current decline (D1), we defined severity as the percentage decline in species richness and plant reproductive output between continuously cattle-grazed and cattle-removed Georgina gidgee woodlands in the north-eastern Simpson Desert where

grazing history had been relatively light (four beasts per 10 km²) (Wilson *et al.* 1990). We calculated the percentage area of *A. georginae* woodlands outside reserves and subject to grazing, based on a minimum convex polygon enclosing all mapped occurrences of *A. georginae*, as for criterion B above, and reviewed changes in species richness and reproductive output of native biota under different grazing pressures.

Ecosystem collapse

For assessment of the geographic distribution in terms of reduction in area or restricted extent, collapse of the Georgina gidgee woodland ecosystem was assumed when the mapped distribution declined to $<10\%$ of its suitable bioclimatic range, with remaining stands exhibiting poor condition and no recruitment. Poor condition is defined as $<10\%$ canopy cover and no new growth. Collapse would likely result from any of the following processes, or combinations thereof: changed hydrological conditions due to altered precipitation and/or increased evapo-transpiration, extraction of ground water, adverse fire regimes, overstocking of livestock or clearing. The interaction of these components is complex, and our thinking draws from our earlier conceptual framework for the broader spinifex grasslands (Dickman *et al.* 2014).

RESULTS

Ecosystem description

The description of Georgina gidgee woodlands is complicated by the paucity of vegetation classification

studies at the appropriate spatial scale and by the need to incorporate fauna into the description. Georgina gidgee woodlands occur within 11 of the 89 bioregions recognized across Australia (Appendixes S1 and S2). A regional ecosystem assessment process for Queensland lists two ecosystems in the Channel Country bioregion where *A. georginae* is a canopy dominant. The first is associated with *Eremophila obovata* ± *Eremophila macdonnellii* tall shrubland on clay plains between sand dunes, the second with *Senna artemisioides* subsp. *oligophylla* ± *Eremophila freelingii* on alluvium. However, outside Queensland no comparable listings exist.

Characteristic native biota

The canopy is dominated by *A. georginae* F. M. Bailey (Fabaceae). Correct identification is important as *A. georginae* has close affinities with *A. cambagei* and is difficult to distinguish if diagnostic reproductive characters, namely the more curved or coiled pods, slightly larger seeds and more hairy petals of *A. georginae*, are absent. There is also some disjunction in the distribution, with *A. cambagei* extending further east into Queensland and south into New South Wales, and being non-toxic to cattle (Peters *et al.* 1965). Georgina gidgee trees (Fig. 1) exhibit a gnarled and spreading habit with variable canopy height (3–8.5 m), resulting in low woodlands or low open woodlands with adult tree densities as high as 200 trees ha⁻¹ but more typically 60–70 trees ha⁻¹. At one site in western Queensland, Georgina gidgee woodlands exhibited a relatively open canopy with a mean vertical depth of 2.9 m, often with distinct browse lines if livestock were present, average total crown cover projections of 4400–5250 m² ha⁻¹ and horizontal distances between individual canopy extents of 4.8–5.0 m (Tischler 2012; Fig. 1).

Georgina gidgee woodlands vary in the structural and floristic composition of the understory. Typically, chenopods, a subfamily now within Amaranthaceae (e.g. *Atriplex* spp., *Sclerolaena* spp., *Halosarcia* spp.), are common, as are grasses and forbs (Frank *et al.* 2014). In some patches, taller shrub layers with *Eremophila* spp. may be present, giving a multi-layered structure. Grasses (*Aristida contorta*, *Dactyloctenium radulans*, several species of *Eragrostis*, *Tragus australianus* and *Yakirra australiensis*) mainly occur after rain, as do forbs (see Appendix S3). There is typically an abrupt boundary between adjoining spinifex grassland and gidgee woodland, visually obvious by the change in structure and floristics despite many species occurring in both habitats, including spinifex itself (Wardle 2010; Frank *et al.* 2014) (Fig. 1).

Georgina gidgee woodlands are important refuge sites for some native rodents, dasyurid marsupials, red

kangaroos and bats (Appendix S4) that have varying levels of reliance on woodland. The sandy inland mouse (*Pseudomys hermannsburgensis*) retreats to woodland patches during dry periods when food resources decline in surrounding spinifex grassland (Dickman *et al.* 2010), while both *Planigale gilesi* and *P. tenuirostris* occur on the clay soils under gidgee (Haythornthwaite & Dickman 2006).

The trees, leaf litter and fallen woody debris in *A. georginae* woodlands provide habitat for many species of reptiles (Pianka 1989; McElhinny *et al.* 2006) (Appendix S4). For example, the semi-arboreal pygmy monitor (*Varanus gilleni*) shelters under loose bark and inside hollows (Wilson & Swan 2003) and uses trees as substrates to hunt invertebrates (Cronin & Oram 2001). Thirteen other reptile species have been recorded in a series of surveys in Georgina gidgee woodlands (Appendix S4). Some of these species, such as the royal ctenotus (*Ctenotus regius*), are seldom found outside the woodland system (Frank 2010). Other species, including long-tailed tree dragons (*Amphibolurus longirostris*) and spiny tailed geckoes (*Strophurus ciliaris*) are tree dependent and confined to woodland patches (Downey & Dickman 1993).

Amphibians appear to use *A. georginae* woodlands for foraging and, when the clay pans contain water for several weeks after rain (Fig. 1), for reproduction, too (Predavec & Dickman 1993). During dry periods, the desert tree frog (*Litoria rubella*) is the only species that may be encountered in woodland, but after rain this species, desert spadefoot frogs (*Notaden nichollsii*) and trilling frogs (*Neobatrachus centralis*) occur, and deeper-burrowing *Cyclorana* spp. may spend several years aestivating under the woodland floor (Predavec & Dickman 1993).

Georgina gidgee woodlands provide permanent or temporary habitat for at least 81 species of birds (Appendix S5). While some core species utilize gidgee as preferred habitat – some exclusively – most birds use the scattered distribution, variable-sized patches and structural attributes of stands as ‘stepping-stones’ through other land systems (Tischler 2012). These patterns are especially evident when episodic rainfalls trigger different floristic responses across disjunct woodlands, resulting in isolated productivity cascades and pockets of resource-rich habitat. Overall, insectivores are the dominant avian functional group in gidgee (Tischler *et al.* 2013), and this ecosystem is preferred habitat for small desert specialists such as banded whiteface (*Aphelocephala nigrificincta*) and hooded robin (*Melanodryas cucullata*) (Tischler 2012).

Singing honeyeaters (*Lichenostomus virescens*) and zebra finches (*Taenopygia guttata*) – examples of common and adaptable desert species – exploit the full range of sub-habitats and breeding sites within Georgina gidgee, along with the crested pigeon (*Ocyphaps lophotes*) and brown falcon (*Falco berigora*)

(Tischler 2012). During resource pulses, Georgina gidgee woodlands provide forage (e.g. seeding grasses, flowering perennial shrubs, invertebrate hatches) and free-standing water in claypans for nomadic granivores such as diamond dove (*Geopelia cuneata*) and budgerigar (*Melopsittacus undulatus*) (Tischler *et al.* 2013).

Invertebrates are a diverse but relatively poorly known component of the Georgina gidgee woodland ecosystem (Fig. 3). Invertebrate orders are similar in number to those in adjoining spinifex habitat, but nearly threefold more numerous in gidgee than spinifex (Appendix S6). As ants are food for some species of reptiles as well as echidnas, ant species richness and composition correlate positively with that of other key invertebrate groups, and ants are known as a reliable bio-indicator species (Andersen *et al.* 2004). Acacia woodlands may also support richer faunas of termites (Isoptera) than spinifex grassland (Morton *et al.* 2011), given the presence of dead wood in tree patches.

In the understory, chenopod shrubs provide preferred forage plants for Lepidoptera (Edwards & Glover 2009). Other groups of note include desert-dwelling cicadas (Hemiptera) (Ewart 2009), semi-

aquatic Coleoptera in flooded claypans (Lemann & Weir 2009) and many soil invertebrates involved in nutrient cycling (Greenslade 2009).

Key processes and interactions

Threatening processes

Six main processes threaten Georgina gidgee woodlands: overgrazing, weeds, feral predators, altered fire regimes, changed hydrological regimes and altered climates. The threatening processes can be viewed collectively as a circle of interacting threats that affect the distribution, biodiversity and ecosystem function of the woodland (Fig. 3). Importantly, given their close proximity, gidgee woodland patches are also functionally connected to the adjoining spinifex grassland (Fig. 3). Each threat will be discussed in turn along with comments on the potential for synergistic effects.

First, overgrazing by livestock may be detrimental to growth and recruitment of the dominant canopy tree. In experimental trials, *A. georginae* did not replace foliage after heavy pruning and defoliation, although growth can occur on heavily grazed trees following rainfall (Robinson *et al.* 1990).

Gidgee woodland patches provide important habitat and resources for cattle (Frank *et al.* 2012) compared to surrounding spinifex: shade and shelter from wind (Bird *et al.* 1992), easy movement on the hard, clay-rich soils, drought forage (gidgee foliage and chenopod shrubs) and understory plants that are more nutritious than in the impoverished spinifex grasslands (Grigg *et al.* 2008).

Red kangaroos increase in abundance in Georgina gidgee woodland in the absence of cattle (Frank 2010), and probably use the woodland for forage, shade and shelter. Introduced herbivores such as camels (*Camelus dromedarius*) and feral horses (*Equus caballus*) potentially degrade biological soil crusts through trampling. Rabbits (*Oryctolagus cuniculus*) are usually uncommon in central arid habitats (Morton 1990) but may still pose a threat as they prevent regeneration of trees and shrubs, particularly species of *Acacia* (Lange & Graham 1983; Friedel 1985; Auld 1995). Camels, by contrast, use mature gidgee foliage as preferred browse (Phillips *et al.* 2001; Dörge *et al.* 2003). Camels also feed selectively on chenopod shrubs and may break gidgee branches while attempting to gain access (authors pers. obs 2011). Camels potentially use over 80% of plant species in desert habitats, over-browse to the point of defoliation, including threatened species and suppress the regeneration of shrubs and trees (Dörge *et al.* 2003). Camel numbers can double every eight years in arid Australia (Edwards *et al.* 2004), placing gidgee woodlands under increasing pressure.

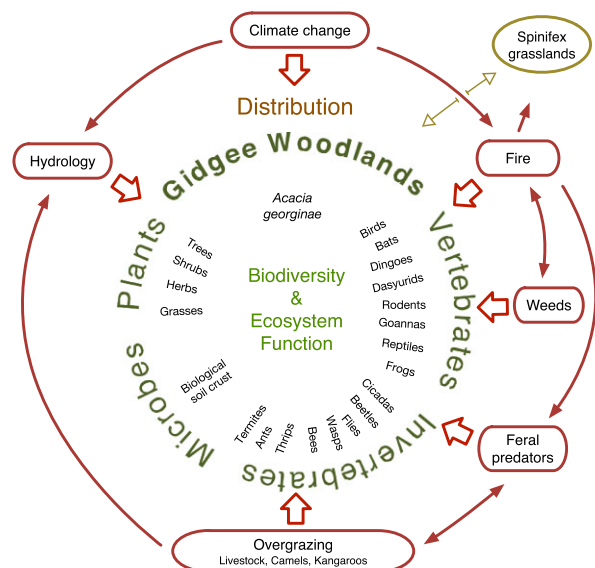


Fig. 3. Conceptual diagram showing the relationship between the key threatening processes (climate change, fire, weeds, feral predators, overgrazing and hydrology) and the geographic distribution and the biodiversity and ecosystem function components of Georgina gidgee woodlands. The main threats to the Georgina gidgee woodland ecosystem are shown in red boxes with large open red arrows. The relationships among the threats are shown in thin red arrows. Key components of the biodiversity mentioned in the text are labelled in the inner circle, but these are not comprehensive. Spinifex hummock grasslands surround most patches of gidgee woodland and, therefore, this close association with another ecosystem is indicated by an open khaki arrow at the top right of the figure.

Second, weeds may become an increasing threat to the persistence of this ecosystem. Since 2007, we have noticed an increase in the distribution and extent of buffel grass (*Cenchrus ciliaris*) in the north-eastern Simpson Desert (authors pers. obs). Buffel grass has the potential to homogenize and smother the open substrate within Georgina gidgee woodlands, a feature that is functionally important to some birds (e.g. chats, Smyth *et al.* 2009) and reptiles (e.g. *Ctenophorus nuchalis*) (Read 2002; Frank 2010). Negative effects of buffel grass on small vertebrates are well known (Grice *et al.* 2013; Young & Schlesinger 2014).

Third, fire is an important process shaping species dynamics and biodiversity in arid vegetation, as it is elsewhere (Turner *et al.* 2008; Bradstock *et al.* 2012). Functional processes, including fire, interconnect adjacent vegetation units to form desert complex environments (Dickman *et al.* 2014). Spinifex burns readily after prolonged and extreme rainfall, as fuel loads can build enough to carry fire (Greenville *et al.* 2009; Nano *et al.* 2012). However, fire does not appear to maintain boundaries between mulga (*Acacia aneura*) and spinifex (Bowman *et al.* 2008; Nano & Clarke 2008); therefore fire may act similarly for gidgee woodlands. Gidgee woodlands rarely burn and, if they do, trees are either killed, or recover after partial scorching (GMW pers. obs). Weeds contribute to altered fire regimes (Clarke *et al.* 2009), with buffel in particular representing a key threat to arid vegetation owing to its high flammability (Butler & Fairfax 2003; Miller *et al.* 2010; Schlesinger *et al.* 2013). Gidgee woodlands are therefore susceptible to changes in the fire regime that will accompany increases in frequency and magnitude of extreme rainfall events across central Australia (Greenville *et al.* 2012).

Fourth, feral predators like red foxes (*Vulpes vulpes*) and feral house cats (*Felis catus*), and occasionally dingoes (*Canis dingo*) find ideal open hunting areas in the sparse ground cover of many woodland patches; feral cats commonly shelter in the shaded canopy of Georgina gidgee (Mahon *et al.* 1998).

Fifth, changed hydrological conditions from water extraction by bores pose a serious threat to Georgina gidgee woodlands and the biodiversity they support (Dickman *et al.* 2014). Permanent water is scarce in this ecosystem; artesian water supports industry and biota alike, but continued extraction of water and diversion of flows is not sustainable (Dickman *et al.* 2014). Georgina gidgee grows on the edge of clay pans that can hold water for months after flooding rains (Fig. 1) but must rely on deeper water otherwise. Destruction of these critical water resources via mining or vehicle impacts on clay pans would have consequences for much of the ecosystem, and for native fauna, as outlined above.

Finally, altered climates pose great threats to woodland biodiversity. Shifts in species ranges track climate

velocities, which are expected to accelerate over the next 50 years (Burrows *et al.* 2014). Increased prevalence of extreme events, including longer droughts, increased floods, higher temperatures and more severe winds and dust storms will further stress ecosystems. Hence, there is an imperative to understand these changes and predict their ecological effects. Aridity and widespread droughts will increase in the next 30–90 years over many areas, resulting from either decreased precipitation and/or increased evaporation (Dai *et al.* 2012). A new rainfall and temperature dynamic may then predominate, and will be evident particularly in regions such as inland Australia with environments shaped by the El Niño Southern Oscillation (ENSO) (Burrows *et al.* 2014).

Risk assessment

Criterion A: decline in distribution

A1 current decline Georgina gidgee was used extensively for fence posts and early buildings, thus thinning woodland stands, but the current distribution is likely to have been in stasis for many decades. Alternative fencing and building materials are now used. The status of the ecosystem is therefore least concern under criterion A1.

A2 future decline Inadequate fine-scale spatial mapping of the distribution limits assessment here, and thus data deficient status is recorded.

A3 historic decline Use of central Australia was limited after European settlement and cattle grazing did not start until the late 19th century (Nolan 2003). Thus, there has been little change in the distribution of Georgina gidgee woodlands. The status of the ecosystem is therefore least concern under criterion A3.

Criterion B: distribution size

B1 extent of occurrence A minimum convex polygon enclosing all mapped occurrences of *A. georginae* (Fig. 2) has an area of 646 562 km². Therefore, the status of this ecosystem is least concern under criterion B1.

B2 area of occurrence Based on records from the Atlas of Living Australia, a total of 269 of the 10 × 10 km cells within the extent of occurrence are occupied by

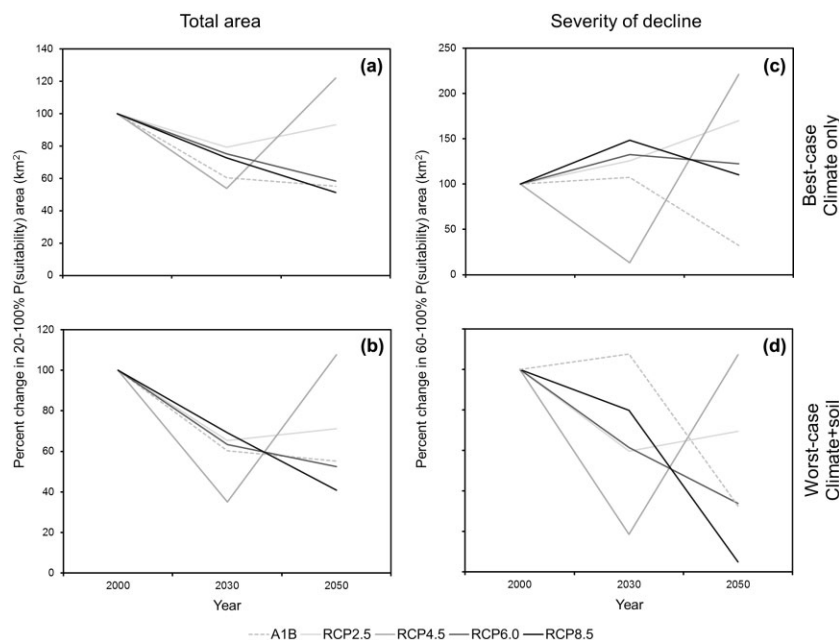


Fig. 4. Predicted change (%) in area of suitable habitat for *Acacia georginae* woodlands over the 50-year period between 2000 and 2050 measured as the change in predicted area of all suitable habitat (where $P(\text{suitability}) \geq 20\%$) for: (a) the best-case, climate-only model; (b) worst-case, climate-and-soil model, for the change in predicted area of high-quality habitat (where $P(\text{suitability}) \geq 60\%$) for (c) the best-case, climate-only model (d) and worst-case, climate-and-soil model.

A. georginae (Appendix S8). Therefore, as this is >50 cells, the status of this ecosystem is least concern under criterion B2.

B3 number of locations From the number of patches in a single locality (Fig. 1) and the number of locations depicted by the independent records in Fig. 2, there are more than five locations, thus warranting classification as least concern under criterion B3.

Criterion C: degradation of abiotic environment

C1 current decline Trends in climate for central Australia show that extreme temperatures (maxima and minima) have increased within the last 50 years, as have the magnitude and frequency of large rainfall events (Greenville *et al.* 2012). Bioclimatic distribution modelling from 2000 using temperature and rainfall variables (see above) suggests that the area of suitable habitat may have increased in the short term for this ecosystem (Appendix S9-13). This has likely been offset by grazing pressure from stock and establishment of rabbits in the drier parts of the continent. However, the emission scenario used for predictions is conservative and, without a global approach to reducing emissions, it may underestimate the trends in extreme weather events and mean climate. With these

cautionary notes, the status of the ecosystem is therefore least concern under criterion C1.

C2 future decline The average test AUC for the models was 0.947 (SD 0.014), suggesting that the models performed better than random (Phillips *et al.* 2006). Predictions of total change in the probability of suitable habitat differed between the AR4 and the updated AR5 climate model (Fig. 4a,b; Table 2), with the A1B scenario of the former most similar to the moderate RCP6.0 scenario of the AR5 model. For the best-case climate-only model, losses ranged from -7% to -59% for AR5 RCP2.6 and AR5 RCP8.5, respectively. Unexpectedly, the least predicted change in area by 2050 was not for the AR5 RCP2.6 scenario but rather the RCP4.5 scenario. Gains were recorded for the medium RCP4.5 scenario (22%) and for all AR5 scenarios (Table 2, Fig. 4). This model exhibits rapid decline to 2030 and then increases to exceed the current area of suitable habitat (Fig. 4a-d). Without further information, however, we are not convinced this scenario is well parameterized as it falls outside the bounds of the lower and higher estimates for emissions.

As expected, the addition of matching soil attributes under the worst-case model further reduced the predicted area of suitable habitat (Fig. 4a,b; Table 2), and the difference between models was most

Table 2. Comparisons of projected change in P(suitability) habitat area for Georgina gidgee woodlands for the period 2000 to 2050 for two climate models, AR4 with one scenario (A1B) and the updated AR5 climate model with four scenarios

Suitable habitat change %		Total change (P > 20%) by 2050		High-quality change (P > 60%) by 2050	
Climate Model	Scenario	Best-case model Climate only	Worst-case model Climate + soil	Best-case model Climate only	Worst-case model Climate + soil
AR4	(A1B scenario)	-45%		-67%	
AR5	RCP				
	2.6 peak 2010–2020	-7%	-29%	+70%	-31%
	4.5 peak 2040	+22%	+8%	+122%	+7%
	6.0 peak 2080	-42%	-47%	+22%	-66%
	8.5 peak end 21st century	-49%	-59%	+10%	-95%
Number of scenarios with ≥50% loss (Criterion C)		0	1	1	2

These representative concentration pathways (RCP) measured in watts per square metre are labelled by the additional energy taken up by the Earth due to extra global annual greenhouse gas emissions (2.6, 4.5, 6.0 and 8.5).

pronounced for scenario RCP2.6 where emissions peak in the short term and other factors may come into play.

The reduction of high-quality habitat under the AR4 model was projected at 67% by 2050. However under AR5 conservative climate-only models, increases between 10% and 122% by 2050 of ≥60% P(suitability) were projected (Table 2; Fig. 4c). By contrast, high-quality habitat decline by 2050 was 31%, 66% and 95% under the RCP2.6, RCP6.0 and RCP8.5 scenarios, respectively (Fig. 4d).

Temporal trends in total suitable habitat and in high-quality habitat were assessed under nine future climate scenarios to give a total of 18 estimates (Table 2). Of these, eight indicate a decline in suitable habitat of less than 30% (i.e. least concern), one is close to 30% (i.e. near threatened), six predict the decline to be between 30% and 50% (i.e. vulnerable), two predict 50–80% (i.e. endangered) and one predicts >80% (i.e. critically endangered) (Fig. 5). Therefore, around half of the scenarios support a least concern status, while the other half support a threatened status, of which vulnerable is the most likely category. From these projections, and given the uncertainty surrounding the RCP4.5 projections, the best estimate of the status of the ecosystem is vulnerable under criterion C2.

C3 historic decline Without quantitative evidence to evaluate if historic changes in climate have reduced *A. georginae* woodland areas since European settlement of Australia, the status under criterion C3 must be data deficient.

Criterion D: altered biotic processes and interactions

D1 current decline Currently, 73% of the extent of Georgina gidgee woodlands is not reserved (473 917 km² from an estimated distribution of 646 562 km², see Criterion B), and hence is potentially exposed to commercial cattle grazing. Available data enable grazing impacts to be quantified (Frank *et al.* 2014), but only from a single *albeit* large region with relatively low grazing intensity, and extrapolations beyond this region, or over a longer time, are uncertain. Within three years of cattle removal and one above-average rainfall event, a 62% decline in plant species composition under grazing was evident (Appendix S3), and plant reproduction declined by 98% (Frank *et al.* 2014). The cover of grasses and sedges was 68% lower in continuously cattle-grazed than cattle-removed gidgee, whereas that of unpalatable mat-forming species like *Tribulus cistoides* and *Indigofera linifolia* was higher in continuously grazed gidgee (Frank *et al.* 2012). Mammal abundance declined by 40%, reptiles by 30% and invertebrates by 35% in continuously grazed gidgee compared to cattle-removed gidgee (Frank *et al.* 2014) (Appendixes S4 and S6). Based on these data, we equate the relative severity of decline in biotic processes to be 30–40% for fauna and 62–98% for flora, and these projected declines in biotic processes occur over 73% of the distribution based on the extent of grazing. Taken together, the declines meet the required level for a designation of vulnerable under criterion D1; namely, relative severity of at least 50–80% over 50–80% of the distribution or declines of at least 30% severity across at least 80% of the distribution (see Keith *et al.* 2013).

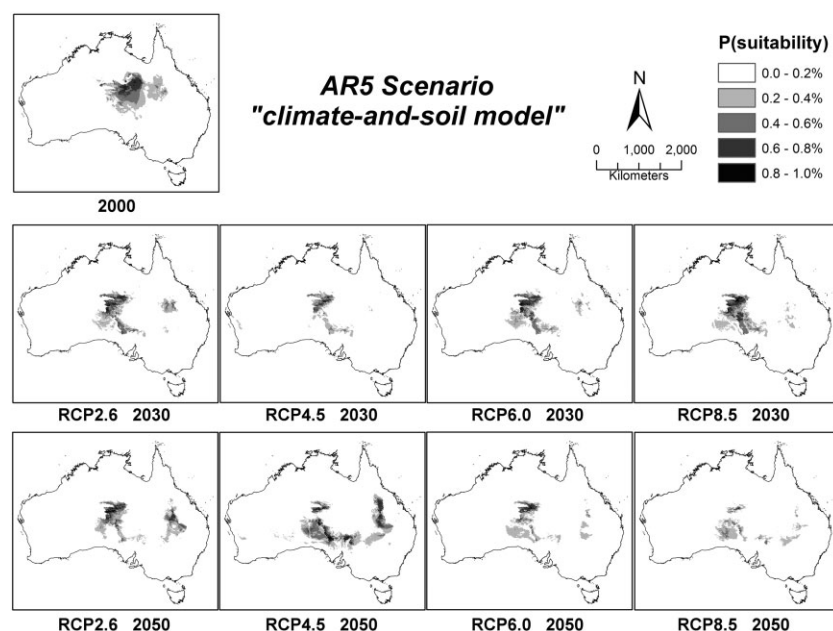


Fig. 5. Extent of predicted suitable habitat for *Acacia georginae* woodlands during the 50-year period between 2000 and 2050. P(suitability) was analysed in Maxent using the four representative concentration pathway scenarios under AR5 climate model. A categorical soil and Australian bioregion layers were also included in these models.

Table 3. Summary of conservation risk assessment of the Georgina gidgee woodland ecosystem under the International Union for the Conservation of Nature criteria

Criterion	A Decline in distribution	B Distribution size	C Degradation of abiotic environment	D Altered biotic processes	E Quantitative risk assessment	Overall risk assessment
Sub-criterion 1	LC	LC	LC	VU	DD	VU
Sub-criterion 2	DD	LC	VU	VU	DD	
Sub-criterion 3	LC	LC	DD	LC	DD	

Letters in bold indicate that assessment determined threatened status. CR, critically endangered; DD, data deficient; EN, endangered; LC, least concern; VU, vulnerable.

We therefore classify the Georgina gidgee woodland ecosystem as vulnerable from the assessment of the biota, but note that uncertainty arises from the need to extrapolate from the available quantitative evidence.

D2 future decline The risk to *A. georginae* woodland areas is that without further protection from grazing through installation of exclusion fences and careful management of stocking rates, water points and total grazing pressure (including camels, rabbits and kangaroos) throughout the rangelands, gidgee will be unable to regenerate and recover from grazing impacts. Based on our results for criterion D1, it is likely that most *A. georginae* woodland areas subject to grazing will fare similarly and should therefore be classified vulnerable under criterion D2.

D3 historic decline Domestic grazing in *A. georginae* woodland areas was very low or negligible prior to the late 1880s and restricted until the 1970s when expansion was undertaken with the use of artificial bores (Nolan 2003; Letnic & Dickman 2006). Therefore, the status of the ecosystem is least concern under criterion D3.

Overall the assessment of Georgina gidgee woodlands is vulnerable based on criteria C2, D1 and D2 (Table 3).

DISCUSSION

We found Georgina gidgee woodland to be vulnerable based on current degradation of the biotic interactions and loss of species due to livestock grazing and

projected future degradation of the abiotic environment with climate change. Two important features related to estimating uncertainties emerged from applying the IUCN protocol of Keith *et al.* (2013) and should guide future work. First, there are extensive knowledge gaps in the current distribution of the ecosystem we studied, including mapping at the appropriate spatial scale, and limited data on the assemblages of biota and how they vary across the geographical range of the ecosystem. Second, our findings highlight the importance of understanding how the various sources of uncertainty combine to either inform or impede successful conservation and management decisions.

To assess risks with more certainty in the future, stronger evidence is needed to establish the response of Georgina Gidgee Woodland to extreme temperature events, extreme rainfall events and prolonged drought. This would provide a basis for refining projections under future climates, reduce uncertainties in the output with a more mechanistic evidence base and provide more direction for planning adaptation strategies. Assessment of biotic degradation requires further exploration of responses to overgrazing to determine if spatial differences detected between grazed and ungrazed treatments represent a long-lasting loss of diversity or whether apparent losses may eventually recover. We also suggest that a more spatially extensive investigation of livestock impacts and densities (perhaps by remote sensing of changes in fractional cover) is needed.

This study has identified substantial knowledge gaps despite the presentation here of the most complete account of Georgina gidgee woodlands to date. An extensive review of the literature, including unpublished reports, yielded mostly brief classifications but little quantitative information. While less than ideal, it was considered important to evaluate current knowledge to spur further work to fill these gaps. To improve our understanding of the ecosystem function, we recommend detailed spatial mapping and analysis coupled with representative plot-based surveys of associated species across the entire distribution.

Globally, there are no ecosystem risk assessments of similar patchily distributed woodlands. The combination of wide geographic extent at a coarse scale, but small patch-size at a fine scale, has contributed to the absence of any mapping or formal description of such woodlands. Ecosystem risk assessments have been completed for similarly patchy ecosystems such as the coastal sandstone upland swamps of New South Wales (Keith *et al.* 2013). In contrast, though, the vegetation of the upland swamps has been extensively mapped (Keith & Myerscough 1993; Tozer *et al.* 2010) and risk assessed (NSW Scientific Committee 2011). For Georgina gidgee woodlands, it has perhaps been a case of 'out of sight, out of mind' as the human population for this region is small (Stafford-Smith & Cribb 2009).

The main driver of environmental degradation is livestock grazing, but the pre-cattle grazing state of Georgina gidgee woodland, and therefore whether some species had been permanently lost, remains unclear. The necessary assumption that observed short-term increases in above-ground presence of plants in ungrazed plots implies a similar loss from grazed areas suggests that caution is warranted. However, cattle grazing reduced the reproductive output of vegetation and promoted cover of unpalatable species. Our results also demonstrated that abundances of most vertebrate taxa were lower where cattle still graze. This should be a warning indicator, considering that once thresholds of grazing pressure have been passed, some species will not persist, leading to irreversible changes in the ecosystem. An example threshold would be if most Georgina gidgee seedlings were lost under grazing pressure, as has happened to other acacia woodland systems in arid Australia (Auld 1995).

This risk assessment for Georgina gidgee woodlands also relies heavily on climate projections, which themselves have multiple sources of uncertainty. The emission scenarios used in global climate projections vary and thus require downscaling to provide regional-level information (Maru *et al.* 2012). Quantifying uncertainty can help, but more work is needed to refine models to account for interactions and feedbacks, particularly for the inter-decadal variability associated with ENSO that affects Australia's climate (Maru *et al.* 2012). To address this, we attempted to bracket the levels of change expected by running several climate scenarios, but we recommend caution in applying the details for decision making until further spatial mapping of locations and appropriate testing of regional downscaling for central Australia has been completed. Nonetheless, given the rapidity of anthropogenic climate change, immediate attention is required to highlight threats and provide direction for future studies. For example, our models suggest that suitable gidgee habitat is predicted to occur in a narrow maximum temperature range of 35–40°C during the warmest month. We have demonstrated that the extent of total suitable habitat loss and the decline of high-quality habitat depend on both the climate model and the future climate scenarios used. Furthermore, we have used soil and bioregions as additional fundamental landscape factors to explore the potential loss of realized habitat for *A. georginae*. Our model AUC values (measures of predictive accuracy) fall under the 'excellent' category as described by Swets (1988), suggesting that our models have good discriminatory power. Additionally, bioclimatic models for species with a relatively limited distribution, such as gidgee, are more likely to have greater precision than for widely distributed species (Segurado & Araujo 2004; Luoto *et al.* 2005).

Our aim was to provide a risk assessment rather than to explore all possible uncertainties in the correlative predictive assessment we used to define areas of habitat suitability for the dominant tree, gidgee. Typical of bioclimatic models, climate was the major limiting factor for the species over a broad geographical extent and, in that sense, we modelled a 'best-case scenario' or the potential magnitude of changes to the suitable habitat of gidgee under future climates. In reality, we would expect the distribution to be patchy with some local extinctions and some populations persisting, the more so if we had access to data for all species in the ecosystem, rather than just the dominant canopy tree. Indeed, we attempted to model a more realistic future prediction by adding important landscape factors in the form of geographic bioregions and soil types. Soil factors, for example, can be more influential than climate in defining the distribution of a species, especially at a local scale (Thuiller 2013).

We also acknowledge three other assumptions not accounted for: dispersal vectors, adaptability and biotic interactions. For example, we have assumed that even if gidgee propagules are dispersed into novel habitats, beyond the climate envelope, they must already possess the necessary attributes to permit establishment in these areas. There is, however, little chance that dispersal into new areas will be possible as the generation time and recruitment window of the dominant trees exceed the period of the dramatic shifts in suitability, and the distances required (100s of kilometres) are not relevant to ant dispersal of seeds or seeds being swept along in rainfall run-off. Even if trees expanded their range, it is not clear that other biota dependent on them would follow. These factors are likely to limit the gidgee ecosystem at a local level, meaning that suitable habitat will be more fragmented than reported here.

While we have classified *A. georginae* woodlands as vulnerable under the C2 criterion, eight of our nine bioclimatic models projected suitable gidgee habitat to decline further by 2070 (data not presented). Although not included in our assessment, we suggest that for ecosystems with long-lived species, such as *A. georginae*, assessments should examine changes to suitable habitat over a longer future period than 50 years.

Future prognosis for the Georgina gidgee woodland ecosystem

The future prognosis of the Georgina gidgee woodland ecosystem, and all species dependent on the resources it provides, is grim if measures to mitigate global climate change are not undertaken. Some of our bioclimatic projections suggest that the area of suitable habitat will decline severely over the next 50 years, but

full ecosystem collapse would take some time to be evident as even dead-standing trees and fallen wooden debris provide some habitat features for fauna that are dependent on these woodland patches. Failure of recruitment of the dominant canopy tree will be similarly difficult to detect for some decades, as it is episodic in response to good rain years. Ecosystem collapse would likely occur synchronously across the distribution, with perhaps more severe effects in the hotter northern regions. Adverse fire regimes and increased weeds will impact recruitment of understory plant species. Additional pressure on this ecosystem would result from an increase in demand for cattle grazing across the rangelands, including marginal areas, to meet the food requirements of the growing human population. Improved knowledge of the fine-scale distribution of the woodlands and the role of altered hydrology across the region would assist in monitoring the status and help to inform suitable management of livestock grazing to minimize impacts, particularly during droughts. Without the shelter and refuge provided by the Georgina gidgee woodlands, small mammals will be under increased pressure from feral predators and will likely move towards extinction on the scale of the critical weight range mammals that have already been lost from most of central Australia (Letnic & Dickman 2006). In summary, despite gidgee woodlands being widespread and remote from the intensive land clearing pressures experienced around coastal Australia, these small woodland patches are classified as vulnerable.

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REFERENCES

- Andersen A. N., Fisher A., Hoffmann B. D., Read J. L. & Richards R. (2004) Use of terrestrial invertebrates for

- biodiversity monitoring in Australian rangelands, with particular reference to ants. *Austral Ecol.* **29**, 87–92.
- Anon (2006) National Vegetation Information System. Australian Government, Department of the Environment and Water Resources, Canberra. [Cited 01/05/15.] Available from URL: <http://www.environment.gov.au/erin/nvis/index.html>
- Auld T. D. (1995) The impact of herbivores on regeneration in four trees from arid Australia. *Rangeland J.* **17**, 213–27.
- Australian Bureau of Meteorology (2014) Average annual and monthly maximum, minimum, and mean temperature. [Cited 10 March 2014.] Available from URL: http://www.bom.gov.au/jsp/ncc/climate_averages/temperature/index.jsp?maptype=3&period=an#maps
- Beadle N. C. W. (1981) *The Vegetation of Australia*. Cambridge University Press, Cambridge.
- Bird P. R., Bicknell D., Bulman P. A. *et al.* (1992) The role of shelter in Australia for protecting soils, plants and livestock. *Agrofor. Syst.* **20**, 59–86.
- Bowman D. M. J. S., Boggs G. S. & Prior L. D. (2008) Fire maintains an *Acacia aneura* shrubland – *Triodia* grassland mosaic in central Australia. *J. Arid Environ.* **72**, 34–47.
- Bradstock R. A., Gill A. M. & Williams R. J., eds (2012) *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World*. CSIRO Publishing, Melbourne.
- Burrows M. T., Schoeman D. S., Richardson A. J. *et al.* (2014) Geographical limits to species-range shifts are suggested by climate velocity. *Nature* **507**, 492–5.
- Butler B. D. W. & Fairfax R. J. (2003) Buffel grass and fire in a gidgee and brigalow woodland: a case study from central Queensland. *Ecol. Manage. Restor.* **4**, 120–5.
- Clarke P. J., Latz P. K. & Albrecht D. E. (2009) Long-term changes in semi-arid vegetation: invasion of an exotic perennial grass has larger effects than rainfall variability. *J. Veg. Sci.* **16**, 237–48.
- Cronin L. & Oram N. (2001) *Australian Reptiles and Amphibians*. Envirobook, Annandale.
- Dai L., Vorselen D., Korolev K. S. & Gore J. (2012) Generic indicators for loss of resilience before a tipping point leading to population collapse. *Science* **336**, 1175–7.
- Department of Environment (2012) Australia's bioregions (IBRA). [Cited 23 August 2012.] Available from URL: <http://www.environment.gov.au/topics/land/national-reserve-system/science-maps-and-data/australias-bioregions-ibra#ibra>
- Dickman C. R., Greenville A. C., Beh C.-L., Tamayo B. & Wardle G. M. (2010) Social organization and movements of desert rodents during population 'booms' and 'busts' in central Australia. *J. Mammal.* **91**, 798–810.
- Dickman C. R., Greenville A. C., Tamayo B. & Wardle G. M. (2011) Spatial dynamics of small mammals in central Australian desert habitats: the role of drought refugia. *J. Mammal.* **92**, 1193–209.
- Dickman C., Wardle G., Foulkes J. & de Preu N. (2014) Desert complex environments. In: *Biodiversity and Environmental Change: Monitoring, Challenges and Direction* (eds D. Lindenmayer, E. Burns, N. Thurgate & A. Lowe) pp. 379–438. CSIRO Publishing, Melbourne.
- Dormann C. F., Elith J., Bacher S. *et al.* (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. *Ecography* **36**, 27–46.
- Downey F. J. & Dickman C. R. (1993) Macro- and microhabitat relationships among lizards of sandridge desert in central Australia. In: *Herpetology in Australia: a Diverse Discipline* (eds D. Lunney & D. Ayers) pp. 133–8. Royal Zoological Society of New South Wales, Sydney.
- Dörge B., Heucke J. & Dance R. (2003) *The Palatability of Central Australian Plant Species to Camels*. Department of Business and Resource Development, Northern Territory Government, Darwin. Technote 116.
- Edwards G. P., Pople A. R., Saalfeld K. & Caley P. (2004) Introduced mammals in Australian rangelands: future threats and the role of monitoring programmes in management strategies. *Austral Ecol.* **29**, 40–50.
- Edwards T. & Glover M. (2009) Butterflies and moths (Lepidoptera) of Cravens Peak Bush Heritage Reserve. In: *Cravens Peak Scientific Study Report. Geography Monograph Series 13* pp. 101–116. The Royal Geographical Society of Queensland, Milton.
- Elith J., Kearney M. & Phillips S. (2010) The art of modelling range-shifting species. *Methods Ecol. Evol.* **1**, 330–42.
- ESRI (2012) ArcGIS 10.1. California, ESRI Inc.
- Ewart A. (2009) Cicadas of the eastern segment of the Cravens Peak Reserve, northeastern Simpson Desert, S.W. Queensland; January/February 2007. In: *Cravens Peak Scientific Study Report. Geography Monograph Series 11* pp. 117–50. The Royal Geographical Society of Queensland Inc, Milton.
- Fensham R. J. & Fairfax R. J. (2005) Preliminary assessment of gidgee (*Acacia cambagei*) woodland thickening in the Longreach district, Queensland. *Rangeland J.* **27**, 159–68.
- Fensham R. J., McCosker J. C. & Cox M. J. (1998) Estimating clearance of *Acacia*-dominated ecosystems in central Queensland using land-system mapping data. *Aust. J. Bot.* **46**, 305–19.
- Foulkes J., de Preu N., Sinclair R., Thurgate N., Sparrow B. & White A. (2014) Chenopod and acacia shrublands. In: *Biodiversity and Environmental Change: Monitoring, Challenges and Direction* (eds D. Lindenmayer, E. Burns, N. Thurgate & A. Lowe) pp. 439–78. CSIRO Publishing, Melbourne.
- Frank A. S. K. (2010) The ecological impacts of cattle grazing within spinifex grasslands and gidgee woodlands in the Simpson Desert, central Australia. PhD thesis, The University of Sydney, Sydney.
- Frank A. S. K., Dickman C. R. & Wardle G. M. (2012) Habitat use and behaviour of cattle in a heterogeneous desert environment in central Australia. *Rangeland J.* **34**, 319–28.
- Frank A. S. K., Dickman C. R., Wardle G. M. & Greenville A. C. (2013) Interactions of grazing history, cattle removal and time since rain drive divergent short-term responses by desert biota. *PLoS ONE* **8**, e68466.
- Frank A. S. K., Dickman C. R., Wardle G. M. & Greenville A. C. (2014) Habitat- and rainfall-dependent biodiversity responses to cattle removal in an arid woodland-grassland environment. *Ecol. Appl.* **24**, 2013–28.
- Free C. L., Baxter G. S., Dickman C. R. & Leung L. K.-P. (2013) Resource pulses in desert river habitats: productivity–biodiversity hotspots, or mirages? *PLoS ONE* **8**, e72690.
- Friedel M. H. (1985) The population structure and density of central Australian trees and shrubs, and relationships to range condition, rabbit abundance and soil. *Rangeland J.* **7**, 130–9.
- Gordon H. B., Rotstayn L. D., McGregor J. L. *et al.* (2002) The CSIRO Mk3 Climate System Model. CSIRO Atmospheric Research Technical Paper No. 60. [Cited 17 May 2015.] Available from URL: http://www.cmar.csiro.au/e-print/open/gordon_2002a.pdf
- Greenslade P. (2009) Soil invertebrate diversity of different landscape units at Cravens Peak with a focus on Collembola.

- In: *Cravens Peak Scientific Study Report. Geography Monograph Series 11* pp. 151–98. The Royal Geographical Society of Queensland Inc, Milton.
- Greenville A. C., Dickman C. R., Wardle G. M. & Letnic M. (2009) The fire history of an arid grassland: the influence of antecedent rainfall and ENSO. *Int. J. Wildland Fire* **18**, 631–9.
- Greenville A. C., Wardle G. M. & Dickman C. R. (2012) Extreme climatic events drive mammal irruptions: regression analysis of 100-year trends in desert rainfall and temperature. *Ecol. Evol. (Amst.)* **2**, 2645–58.
- Grice A. C., Vanderduys E. P., Perry J. J. & Cook G. D. (2013) Patterns and processes of invasive grass impacts on wildlife in Australia. *Wildl. Soc. Bull.* **37**, 478–85.
- Grigg A. M., Veneklaas E. J. & Lambers H. (2008) Water relations and mineral nutrition of closely related woody plant species on desert dunes and interdunes. *Aust. J. Bot.* **56**, 27–43.
- Haythornthwaite A. S. & Dickman C. R. (2006) Distribution, abundance, and individual strategies: a multi-scale analysis of dasyurid marsupials in arid central Australia. *Ecography* **29**, 285–300.
- Hijmans R. J., Cameron S. E., Parra J. L., Jones P. G. & Jarvis A. (2005) Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25**, 1965–78.
- Isbell R. F. (2002) *The Australian Soil Classification*, Revised Edition. CSIRO Publishing, Melbourne.
- IUCN (2014) Threats Classification Scheme (Version 3.2). [Cited 17 May 2015.] Available from URL: <http://www.iucnredlist.org/technical-documents/classification-schemes/threats-classification-scheme>
- Jeffrey S. J., Rotstayn L. D., Collier M. A. *et al.* (2013) Australia's CMIP5 submission using the CSIRO Mk3.6 model. *Aust. Meteorol. Oceanogr. J.* **63**, 1–13.
- Johnson R. W. & Burrows W. H. (1981) *Acacia* open-forests, woodlands and shrublands. In: *Australian Vegetation* (ed. R. H. Groves) pp. 198–226. Cambridge University Press, Cambridge.
- Keith D. A. & Myerscough P. J. (1993) Floristics and soil relations of upland swamp vegetation near Sydney. *Aust. J. Ecol.* **18**, 325–44.
- Keith D. A., Rodríguez J. P., Rodríguez-Clark K. M. *et al.* (2013) Scientific foundations for an IUCN Red List of Ecosystems. *PLoS ONE* **8**, e62111.
- Lange R. T. & Graham C. R. (1983) Rabbits and the failure of regeneration in Australian arid zone *Acacia*. *Aust. J. Ecol.* **8**, 377–81.
- Lemann C. & Weir T. (2009) Baseline study of the beetles (Insecta: Coleoptera) of Cravens Peak Station area. In: *Cravens Peak Scientific Study Report. Geography Monograph Series 11* pp. 253–72. The Royal Geographical Society of Queensland Inc, Milton, QLD.
- Letnic M. & Dickman C. R. (2006) Boom means bust: interactions between the El Niño/Southern Oscillation (ENSO), rainfall and the processes threatening mammal species in arid Australia. *Biodivers. Conserv.* **15**, 3847–80.
- Levin N., Levental S. & Morag H. (2012) The effect of wildfires on vegetation cover and dune activity in Australia's desert dunes: a multisensor analysis. *Int. J. Wildland Fire* **21**, 459–75.
- Lindenmayer D., Burns E., Thurgate N. & Lowe A. (2014) *Biodiversity and Environmental Change: Monitoring, Challenges and Direction*. CSIRO Publishing, Melbourne.
- Luoto M., Pöyry J., Heikkinen R. K. & Saarinen K. (2005) Uncertainty of bioclimate envelope models based on the geographical distribution of species. *Global. Ecol. Biogeogr.* **14**, 575–84.
- McElhinny C., Gibbons P., Brack C. & Bauhus J. (2006) Fauna-habitat relationships: a basis for identifying key stand structural attributes in temperate Australian eucalypt forests and woodlands. *Pac. Conserv. Biol.* **12**, 89–110.
- Mahon P. S., Banks P. B. & Dickman C. R. (1998) Population indices for wild carnivores: a critical study in sand-dune habitat, south-western Queensland. *Wildl. Res.* **25**, 11–22.
- Maru Y. T., Chewings V. & Sparrow A. (2012) Climate change adaptation, energy futures and carbon economies in remote Australia: a review of the current literature, research and policy. CRC-REP Working Paper CW005. Ninti One Limited, Alice Springs.
- Miller G., Friedel M., Adam P. & Chewings V. (2010) Ecological impacts of buffel grass (*Cenchrus ciliaris* L.) invasion in central Australia – does field evidence support a fire-invasion feedback? *Rangeland J.* **32**, 353–65.
- Morton S. R. (1990) The impact of European settlement on the vertebrate animals of arid Australia: a conceptual model. *Proc. Ecol. Soc. Aust.* **16**, 201–13.
- Morton S. R., Stafford Smith D. M., Dickman C. R. *et al.* (2011) A fresh framework for the ecology of arid Australia. *J. Arid Environ.* **75**, 313–29.
- Nano C. E., Clarke P. & Pavey C. R. (2012) Fire regimes in arid hummock grasslands and *Acacia* shrublands. In: *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World* (eds R. A. Bradstock, A. M. Gill & R. J. Williams) pp. 195–214. CSIRO Publishing, Melbourne.
- Nano C. E. M. & Clarke P. J. (2008) Variegated desert vegetation: covariation of edaphic and fire variables provides a framework for understanding mulga-spinifex coexistence. *Austral Ecol.* **33**, 848–62.
- Nolan C. (2003) *Sand hills and Channel Country*. Diamantina Shire Council, Bedourie.
- NSW Scientific Committee (2011) *Final Determination to List Coastal Upland Swamp as an Endangered Ecological Community under the Threatened Species Conservation Act 1995*. Government of New South Wales, Sydney.
- Peters R. A., Murray L. R. & Shorthouse M. (1965) Fluoride metabolism in *Acacia georginae* Gidyea. *Biochem. J.* **95**, 724–30.
- Phillips A., Heucke J., Dörge B. & O'Reilly G. (2001) *Co-Grazing Cattle and Camels*. Rural Industries Research and Development Corporation, Kingston.
- Phillips S. J., Anderson R. P. & Schapire R. E. (2006) Maximum entropy modeling of species geographic distributions. *Ecol. Modell.* **190**, 231–59.
- Phillips S. J. & Dudik M. (2008) Modelling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* **31**, 161–75.
- Pianka E. R. (1989) Desert lizard diversity: additional comments and some data. *Am. Nat.* **134**, 344–64.
- Predavec M. & Dickman C. R. (1993) The ecology of desert frogs: a study from south-western Queensland. In: *Australian Herpetology: A Diverse Discipline* (eds D. Lunney & D. Ayers) pp. 159–69. Royal Zoological Society of New South Wales, Sydney.
- Purdie R. L. (1984) Land systems of the Simpson Desert region. Natural resources series no. 2. CSIRO Division of Water and Land Resources, Melbourne.
- Raghu S., Nano C. E. M. & Pavey C. R. (2013) A demographic framework for the adaptive management of the endangered arid-zone tree species *Acacia peuce*. *Aust. J. Bot.* **61**, 89–101.

- Ramankutty N. & Foley J. A. (1999) Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochem. Cycles* **13**, 997–1027.
- Read J. L. (2002) Experimental trial of Australian arid zone reptiles as early warning indicators of overgrazing by cattle. *Austral Ecol.* **27**, 55–66.
- Robinson D., Maconochie J. & Hanna P. (1990) Effects of rain-fall and simulated browsing on the growth of *Acacia georginae* (F.M. Bailey) in arid central Australia. *Rangeland J.* **12**, 79–83.
- Schlesinger C., White S. & Muldoon S. (2013) Spatial pattern and severity of fire in areas with and without buffel grass (*Cenchrus ciliaris*) and effects on native vegetation in central Australia. *Austral Ecol.* **38**, 831–40.
- Segurado P. & Araujo M. B. (2004) An evaluation of methods for modelling species distributions. *J. Biogeogr.* **31**, 1555–68.
- Smyth A., Friedel M. & O'Malley C. (2009) The influence of buffel grass (*Cenchrus ciliaris*) on biodiversity in an arid Australian landscape. *Rangeland J.* **31**, 307–20.
- Smyth A. K., Hilbert D. W., Ferrier S. *et al.* (2012) The implications of climate change for biodiversity conservation and the National Reserve System: hummock grasslands biome. CSIRO Climate Adaptation Flagship Working Paper No. 13D.
- Stafford-Smith M. & Cribb J. (2009) *Dry Times: Blueprint for a Red Land*. CSIRO Publishing, Melbourne.
- Swets J. A. (1988) Measuring the accuracy of diagnostic systems. *Science* **240**, 1285–93.
- Thuiller W. (2013) On the importance of edaphic variables to predict plant species distributions – limits and prospects. *J. Veg. Sci.* **24**, 591–2.
- Tischler M. (2012) Bird responses to habitat and resource pulses in the Simpson Desert, Central Australia. PhD Thesis, University of Sydney, Sydney.
- Tischler M., Dickman C. R. & Wardle G. M. (2013) Avian functional group responses to rainfall across four vegetation types in the Simpson Desert, central Australia. *Austral Ecol.* **38**, 809–19.
- Tozer M. G., Turner K., Keith D. A. *et al.* (2010) Native vegetation of southeast NSW: a revised classification and map for the coast and eastern tablelands. *Cunninghamia* **11**, 359–406.
- Turner D., Ostendorf B. & Lewis M. (2008) An introduction to patterns of fire in arid and semi-arid Australia, 1998–2004. *Rangeland J.* **30**, 95–107.
- van Vuuren D. P., Edmonds J., Kainuma M. *et al.* (2011) The representative concentration pathways: an overview. *Clim. Change* **109**, 5–31.
- Wardle G. M. (2010) The story of our land revealed through plants. In: *Desert Channels: The Impulse to Conserve* (eds L. Robin, C. R. Dickman & M. Martin) pp. 90–105. CSIRO Publishing, Melbourne.
- Wilson P. R., Purdie R. & Ahern C. R., eds (1990) *Western Arid Region Land Use Study*. Division of Land Utilisation, Brisbane.
- Wilson S. K. & Swan G. (2003) *A Complete Guide to Reptiles of Australia*. Reed New Holland, Sydney.
- Young L. & Schlesinger C. (2014) Habitat use and behaviour of birds in areas invaded by buffel grass (*Cenchrus ciliaris* L.) and in restored habitat. *Wildl. Res.* **41**, 379–94.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. List of bioregions where Georgina gidgee woodlands are known to occur.

Appendix S2. Map of known locations of Georgina gidgee woodlands.

Appendix S3. Plant species in gidgee woodland in the Simpson Desert.

Appendix S4. Fauna species recorded in gidgee woodlands.

Appendix S5. Bird species recorded in Georgina gidgee woodlands of the NE Simpson Desert.

Appendix S6. Invertebrate occurrence from a series of surveys in gidgee woodlands.

Appendix S7. References for biogeographic data.

Appendix S8. Minimum convex polygon enclosing all mapped occurrences of *A. georginae*.

Appendix S9. Bioclimatic modelling of *Acacia georginae*.

Appendix S10. Relative contributions of variables from worst-case climate and soil model of *Acacia georginae* distribution.

Appendix S11. Map of extent of predicted suitable habitat for gidgee up to 2050 using the AR4 A1B climate scenario.

Appendix S12. Map of extent of predicted suitable habitat for gidgee up to 2050 using the AR5 climate scenario.

Appendix S13. References for distribution mapping.