

Herbivore management for biodiversity conservation: A case study of kangaroos in the Australian Capital Territory (ACT)

By Iain Gordon , Melissa Snape , Don Fletcher, Brett Howland , Graeme Coulson , Marco Festa-Bianchet , Peter Caley, Sue McIntyre, Tony Pople, Claire Wimpenny , Greg Baines and Doug Alcock

Populations of macropods are higher than estimated pre-European densities in many parts of Australia. To achieve appropriate densities of macropods in the Australian Capital Territory's nature reserves, multi-tenure kangaroo management units are used to tailor management of kangaroos and total grazing pressure to achieve conservation objectives. An adaptive management framework is recommended that monitors the state of the ground-layer vegetation and alters the cull accordingly. This case study may provide insights for kangaroo management in other temperate areas of Australia.

Key words: culling, kangaroo management units, modelling, safe operating environment.

Iain Gordon and **Sue McIntyre** are Honorary Professors with the Fenner School of Environment and Society, the Australian National University (- Canberra ACT, Australia; Email: iain.Gordon@anu.edu.au). **Melissa Snape**, **Claire Wimpenny** and **Greg Baines** are ecologists with Conservation Research (Australian Capital Territory Government, Canberra, ACT, Australia). **Don Fletcher** is an independent researcher. **Brett Howland** is an ecologist with Parks and



Figure 1. Kangaroo grazing, particularly during drought, can result in significant loss of grassy layer habitat. Photo by Melissa Snape.

Conservation Service (Australian Capital Territory Government, Canberra, ACT, Australia). **Graeme Coulson** is an Honorary Principal Fellow with the School of BioSciences (The University of Melbourne, Melbourne, Victoria, Australia). **Marco Festa-Bianchet** is Chair of the Département de biologie (Université de Sherbrooke, Sherbrooke, Québec, Canada). **Peter Caley** is Principal Research Scientist, with Data61 (CSIRO, Canberra, ACT, Australia). **Tony Pople** is Principal Scientist with Department of Agriculture and

Fisheries (Queensland Government, Brisbane, Queensland, Australia). **Doug Alcock** is a professional agriculturalist with Graz Prophet Consulting (New South Wales, Australia).

Introduction

Large mammalian herbivores have a long co-evolutionary relationship with the plants that share their habitat

Adaptations in animal anatomy, physiology and behaviour are related to the plants upon which they feed (e.g. Gordon & Prins, 2019), whilst plants have evolved structural and chemical defences against herbivory and may also respond to herbivore-driven nutrient cycling (e.g. deposition of faeces and urine; Gordon & Prins, 2019). Over ecological time, large herbivores are a significant factor influencing plant population dynamics, vegetation community composition and structure, the faunal diversity associated with these vegetation communities, as well as the intensity and frequency of fires (Gordon & Prins, 2019). As such, the individual and combined influences of herbivore species' feeding behaviour within an ecosystem, as well as their relative population densities, can affect ecosystem processes and services, and the biodiversity that relies on vegetation for food and cover (Owen-Smith 2002; Augustine *et al.* 2003; Fynn *et al.* 2016).

Over recent millennia, humans have extirpated or significantly reduced the impacts of carnivores in many ecosystems (Ritchie *et al.* 2012; Ripple *et al.* 2014). The resulting release of prey species' populations from these top-down effects has had profound consequences for the regulation of herbivore population densities (Prowse *et al.* 2014). Reductions in perceived predation risk have also increased the extent of foraging areas readily utilised by herbivores (Ripple & Beschta, 2004). Combined, these direct and indirect changes have skewed ecological plant–herbivore processes worldwide from their original evolutionarily 'co-adapted' state (Augustine & McNaughton, 1998; Ripple & Beschta, 2004).

In Australia, the native Thylacine (*Thylacinus cynocephalus*) was eliminated from the mainland about 5,000 years ago. Livestock grazing was introduced over extensive areas of the continent following settlement by Europeans ~ 250 years ago, after

which the Dingo (*Canis dingo*) was eliminated from much of the mainland, and Indigenous hunting was suppressed (Prowse *et al.* 2014; Johnson 2015). This combination of actions is believed to have reduced predation/hunting pressure on the larger marsupial herbivores, and in combination with land clearing and the promotion of grass growth, has led to significant increases in the distribution and density of many large macropod species, notably the Eastern Grey Kangaroo (*Macropus giganteus*), Western Grey Kangaroo (*M. fuliginosus*), Red Kangaroo (*Osphranter rufus*) and a number of the larger wallaby species (Wilson & Edwards, 2019).

These changes in macropod distribution and abundance have led to significant impacts on agricultural pasture, and native vegetation communities and their associated fauna (Fig. 1; Howland *et al.* 2014; Prowse *et al.* 2014). Densities of a number of species of macropods remain above pre-European densities in many areas, despite most Australian states (except Tasmania) having a commercial harvest of kangaroos, all states and territories allowing licensed shooters to cull kangaroos on their properties to reduce total grazing pressure, and some jurisdictions allowing conservation culls (Wilson & Edwards, 2019).

The Australian Capital Territory (ACT) Government undertakes an annual 'conservation cull' of kangaroos within the urban reserves comprising Canberra Nature Park. The objective of this programme is to achieve densities of kangaroos that provide a grazing regime favourable for the conservation of the plants and animals that occur in the ground-layer vegetation. Here, we will review the history of the kangaroo management programme in conservation reserves of the ACT, describe the current management policy enacted by the ACT Government, and provide recommendations for future management of kangaroos and total grazing pressure to achieve conservation

objectives in the ACT. This follows an Expert Workshop (attended by the authors of this paper, and other ACT Government staff) organised by the ACT Government's Conservation Research unit and held in Canberra, ACT, in August 2018, to discuss and review recent research relating to the management of kangaroo grazing in the ACT's nature reserves.

Kangaroo Management in the Australian Capital Territory (ACT)

The context: Canberra Nature Park

Canberra Nature Park is a network of 37 nature reserves dispersed throughout the city of Canberra, ACT. Individual nature reserves range in size from 47 to 2017 ha, with a total combined area of around 11,000 ha. Individual reserves within this network, whilst connected at the landscape scale, are fragmented at the finer scale by lakes and rivers, as well as anthropomorphic barriers such as suburbs, fences and major roads. Green corridors, and other natural or semi-natural spaces such as golf courses, urban parks and farmland, also contribute to habitat connectivity for some species throughout the ACT's urban matrix. The management goals for Canberra Nature Park are to conserve the natural environment, and to provide for public use for recreation, education and research (ACT Government 2019a).

The grasslands, woodlands and forests of Canberra Nature Park are of conservation significance, both regionally and nationally, due to the size and connectivity of these patches throughout the landscape. Over one third of the reserve system supports critically endangered Yellow Box – Blakeley's Red Gum Grassy Woodland, and a further 10 per cent supports critically endangered Natural Temperate Grassland or habitat for eighteen threatened grassland animals or plants (ACT Government 2019a).

The herbivore: Eastern Grey Kangaroo

By far, the largest and most abundant of the indigenous vertebrates in the ACT is the Eastern Grey Kangaroo (hereafter kangaroo) (Box 1, Fig 3). The other three extant macropod species (Black Wallaby, *Wallabia bicolor*; Red-necked Wallaby, *Notamacropus rufogriseus*; and Common Wallaroo, *Osphranter robustus*) have increased substantially in distribution and abundance in the last four decades (D. Fletcher pers obs. since 1975), but none has been subject to licensed culling. Kangaroos are responsible for the majority of herbivory in Canberra Nature Park (ACT Government 2019b), and as such they occupy a central place in the ecology of these ecosystems (ACT Government 2010). They are also treasured by Canberrans as one of the best-known local native animal species (Micromex Research 2008). Kangaroos had been almost extirpated from the area where Canberra was to be built but began to increase from the early 1950s (ACT Government 2010). In 1975, only two reserves or future reserves of Canberra Nature Park appeared to contain kangaroos, but in 2020 kangaroos are obvious in all 37, and are also present in some of the larger suburban parks. Areas of kangaroo habitat within the urban matrix of the ACT are linked by green corridors; consequently, additional urban parks are continuing to be colonised by the species (Fletcher pers obs. since 1975). At the same time, kangaroos are being displaced from areas of former habitat by urban expansion. It is apparent that kangaroos are now more abundant in the Australian Capital Territory than at any time since 1900 but pre-European abundance is unknown because explorer accounts are ambiguous or equivocal.

Grazing pressure in the ACT reserves

Heavy grazing pressure, associated with high-density kangaroo

Box 1. The Herbivore: Eastern Grey Kangaroo

The Eastern Grey Kangaroo (*Macropus giganteus*) exhibits a highly seasonal breeding pattern in the ACT, with 84 per cent of young born within three months of the third week of November (Fig. 3; Fletcher 2006). Final pouch emergence generally occurs in spring around 9.6 months later. Fecundity is as high as 83 per cent even in dry years, and typically 71 per cent of adults are females although the birth ratio is even (Fletcher 2006). The principal limit to kangaroo abundance for unmanaged populations is food availability, which acts mainly through juvenile mortality due to starvation or related processes (Fletcher 2006, 2007; Portas & Snape, 2018). Kangaroos are also preyed upon, and scavenged by, Dingoes (*Canis dingo*), Wedge-tailed Eagle (*Aquila audax*), European Red Fox (*Vulpes vulpes*), and a variety of carrion-associated invertebrate species (Robertshaw & Harden, 1989; Barton *et al.* 2013). They are also frequently killed through collisions with motor vehicles, especially during late winter and early spring, with an estimated 13,985 kangaroo-vehicle collisions occurring on ACT roads in 2015, based on the results of Micromex Research (2015), and the number of licensed drivers in the ACT. High collision rates also apply in a large adjoining region of NSW (Ramp & Roger 2008). The effects of fences on predation and vehicle-related mortalities appears to influence population growth rates of kangaroos (Table 1).

populations, can cause loss of herbaceous biomass (McIntyre *et al.* 2010), and local loss of threatened

plant and animal species (Coulson 2001, 2006; Howland *et al.* 2014, 2016a). Specifically, selective grazing by kangaroos in the ACT has been demonstrated to modify the habitats of grassland plants, birds, reptiles and invertebrates (Barton *et al.* 2011; Howland *et al.* 2014, 2016b; McIntyre *et al.* 2018). For example, by maintaining a short grass structure, kangaroos reduce the density of, or exclude, certain grassland birds (Neave & Tanton, 1989), and grazing-sensitive plants (McIntyre *et al.* 2018). Grazing lawns can also have high floristic diversity and may, concurrently, benefit floristic diversity at some scales (Vivian & Godfree, 2014; Snape *et al.* 2018). Efforts in Canberra Nature Park to reverse the effects of historic heavy livestock grazing, and ongoing kangaroo grazing, show only modest recovery of grazing-sensitive species, and document a perennial flora that is resistant to change, even after four years of favourable rainfall and reduced grazing pressure (McIntyre *et al.* 2010, 2017). It should be noted that localised species losses would likely be permanent within the fragmented grassy ecosystems of Canberra Nature Park; therefore, a consistent landscape scale approach to the management of kangaroo populations is essential for the conservation of endangered ecological communities in this context.

The policy: Program history and development of a kangaroo management plan

The history of the programme is summarised in Fig. 2.

The conservation cull of kangaroos within Canberra Nature Park aims to maintain densities of kangaroos which allow for conservation of the grassy ecological community and habitat for all grassland plant and animal species. This objective, along with significant reference to the scientific literature which underpinned kangaroo management policies, was first described

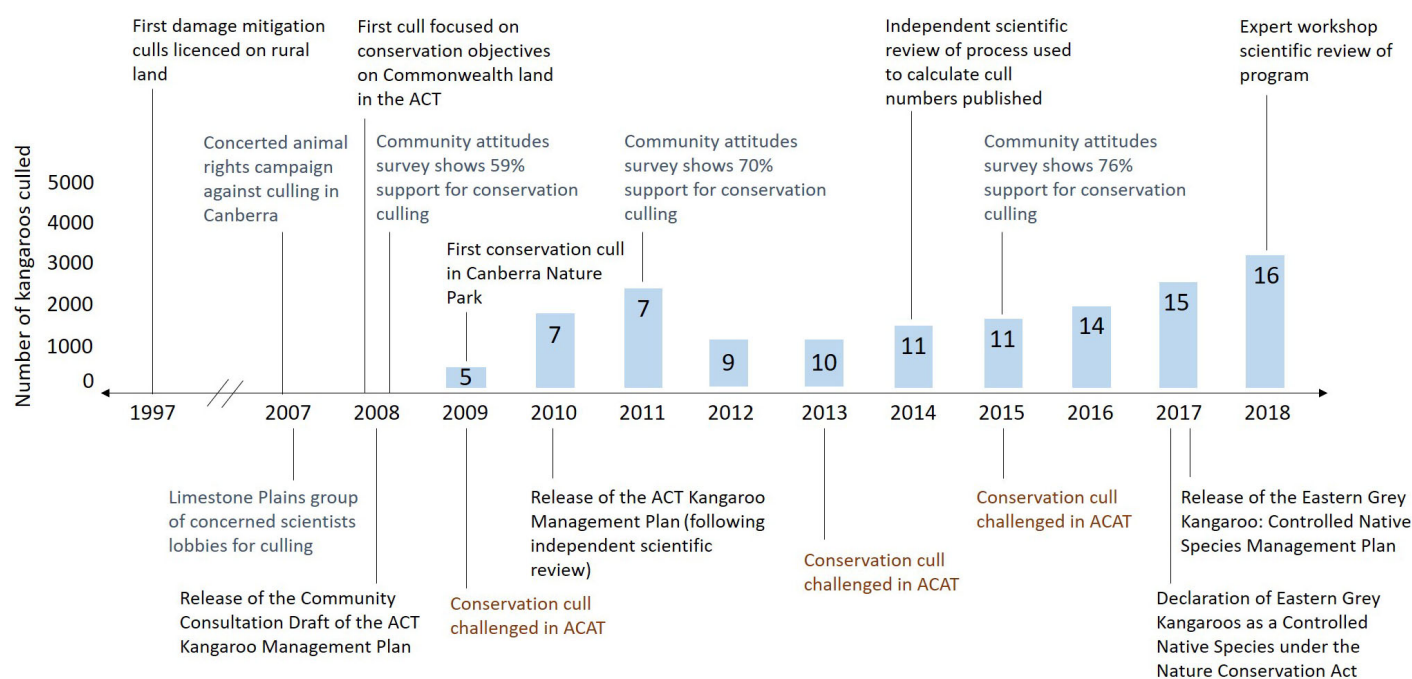


Figure 2. Timeline showing a summarised history of the conservation culling programme delivered by ACT Government. Bars show the number of animals culled during the conservation cull programme each year; the number within the bars shows the number of sites being managed through the programme in that year (including sites in the 'maintenance' stage where little or no culling was required to maintain target densities from year to year).

in the *ACT Kangaroo Management Plan* (ACT Government 2010).

The scale of the ACT conservation culling programme was kept deliberately small in its first year (494 kangaroos in five reserves) in recognition of the rigorous standards required for shooting in urban areas, and that this was a novel activity for those responsible (Fletcher pers obs., ACT Government 2017). A kangaroo shooting season from March to July (the austral winter) was also enforced to reduce the rate at which shooters encounter female kangaroos with a young-at-foot or large pouch young that would be deprived of maternal milk and face starvation if its mother was culled (Fig. 3; Fletcher 2007). However, substantial opposition to culling remained in some sectors of the Australian community (Ballard 2008; Micromex 2008, 2012, 2015; ACAT 2009, 2014; Ben-Ami & Mjadwesch, 2017), although kangaroo culling was supported by many if it reduces kangaroo deaths due to starvation or to meet conservation objectives (Sharp 2012).

The culling programme encountered significant resistance initially, within and outside ACT Government, and from 'The Canberra Times', the primary local newspaper. An important factor in overcoming this challenge was the formation of the 'Limestone Group' of Canberra-based scientists and conservation group representatives who provided supportive commentary independent of government (Fig. 2).

Court injunctions delayed the programme in three of its first six years until legal appeals were heard and lost. The appeals ostensibly targeted the ecological evidence underpinning the culling programme (e.g. validity of counting methods, or evidence that the abundance of one native species might impact that of another (ACAT 2009, 2014)), although the three individuals nominally responsible for the appeals have stated their underlying motivation to be opposition to the killing of sentient individual animals. When the cull re-commenced, protestors cut fences, glued up padlocks on scores of gates, and on one occasion

slashed tyres and smashed windows at two ACT Government depots, actions publicly defended by two of the most prominent protestors (Fig. 4; Canberra Times 2014a,b). Community support for the protest appeared to decline suddenly after this vandalism, as it had done previously in response to vandalism of a fox-proof fence protecting eastern bettong (*Bettongia gaimardi*) recently re-introduced to the mainland (The RiotACT 2012), and the detention of two university researchers (Francis 2012) who were mistaken for kangaroo shooting personnel. Meanwhile, government efforts to explain the conservation cull, mainly on web pages and in the news media, were increased to include a wide range of media. This included some actions regarded as unusually bold for government media units and ministerial offices; for example, a novelist was given access to every part of the shooting operation, resulting in a more informed and objective treatment in the resulting Canberra-based novel (Viggers 2015). Also, a

documentary film crew was allowed to accompany government scientists for one year of their daily activities, whilst also recording the thoughts and activities of kangaroo activists (360 Degree Films 2011). Protest declined and after 2015, protests at cull sites became insignificant. By 2017, 14 of the 37 conservation reserves in Canberra (and one ACT Government managed reserve in NSW) had been involved in the conservation culling programme at least once, and the operational capacity, and geographical extent, of the programme had increased significantly (Fig. 2).

Resulting policy

In recognition of the ongoing requirement for kangaroo management in the ACT, the Eastern Grey Kangaroo was declared a 'Controlled Native Species' under the *ACT Nature Conservation Act 2014* in 2017, negating the need for the ACT Government to obtain a licence to undertake annual kangaroo management programmes. In the same year, an *Eastern Grey Kangaroo: Controlled Native Species Management Plan* (ACT Government 2017) was published as a statutory plan under the *ACT Nature Conservation Act 2014*, reaffirming the policy objectives identified in the *ACT Kangaroo Management Plan*, namely to:

- Maintain populations of kangaroos as a significant part of the fauna of the 'bush capital' and a component of the grassy ecosystems of the Territory;
- Manage and minimise the environmental, economic and social impacts of those kangaroo populations on other biota, grassy ecosystems and primary production.

Since the initiation of the conservation culling programme, when 59 per cent of the public were 'supportive' or 'very supportive' of conservation culling, public acceptance increased (70 per cent in 2011) then remained



Figure 3. Management of appealing species like eastern grey kangaroos needs to be soundly based to withstand public scrutiny. Photo by Don Fletcher.

high (76 per cent in 2015) according to repeated community attitude surveys (Micromex Research 2012, 2015).

The approach: kangaroo management units and an annual culling program

The *ACT Kangaroo Management Plan* gave significant consideration to the spatial and temporal scale of the conservation culling programme (ACT Government 2010). A major outcome was the identification of individual Kangaroo Management Units (or KMUs), which were defined as areas occupied by a discrete kangaroo population bounded by barriers to kangaroo movement (determined through GPS tracking studies) such as high-speed roads (≥ 80 km/h limit), significant water bodies or suburbs (Tolfts 2019; ACT Government unpublished data; Fig. 5). As many nature reserves are only 2–3 km² in area and are bounded, on at least one side, by other open spaces, such as rural properties, golf courses or horse agistment paddocks, some kangaroo home ranges straddle the boundary between the reserve and adjoining land.

Consequently, the multi-tenure KMU approach was adopted such that temporary movements of individual kangaroos into and out of a nature reserve, especially in relation to disturbance such as counting or culling activities (Pulsford & Snape 2019), would not impact on the capacity of land managers to undertake effective monitoring and management of the broader isolated kangaroo population. Overall, culling targets across all land tenures within the KMU were subdivided between landholders (e.g. ACT Parks and Conservation Service, rural leases and horse agistment operators). For legal reasons, licences to cull kangaroos were issued to landholders individually but there was mutual value in cooperative management given the shared nature of the kangaroo population within each KMU.

In many cases, new KMUs that were incorporated into the conservation culling programme required large initial reductions in kangaroo density to reach conservation targets, sometimes taking multiple years to achieve the target (Fig. 6). After kangaroo populations were reduced, they could usually be maintained at the reduced size thereafter by small annual culls.

Table 1. Average annual kangaroo population growth rates in Canberra

Site	Elapsed years	Final year	Exponential annual growth rate r	% annual growth rate	Notes
The Pinnacle KMU	3	2014	-0.02	-2%	Minor culls included
Mt Painter KMU	2	2014	0.00	0%	
Farrer Ridge NR	3	2014	0.00	0%	
Googong	4	2013	0.04	4%	
Confidential Site A, Period 1	8	2009	0.13	14%	
Mulanggari KMU	5	2013	0.14	15%	Minor cull included
Gungaharra KMU	1	2014	0.15	16%	
Jerrabomberra East KMU	6	2014	0.16	17%	
Crace NR	3	2014	0.25	28%	
Confidential Site B, Period 2*	7	2013	0.26	29%	*
Wanniassa Hills KMU	4	2013	0.28	32%	
Confidential Site B, Period 1*	3	2008	0.30	36%	*
Red Hill	2	2012	0.34	40%	
Mulligans Flat Sanctuary †	3	2011	0.34	40%	†

Population growth rates (PGR) have been averaged over the stated time periods (1 to 8 years) when there was little or no deliberate interference such as culling (two exceptions are noted where the natural PGR may have been greater than the values stated). The table is sorted in order of PGR. Unnamed sites are on private property.

*Fenced site lacks motor vehicle collisions, dogs, dispersal.

†Fenced site lacks motor vehicle collisions, dogs, foxes, dispersal.



Figure 4. Protestors and security guards struggle beside a car carrying students researching kangaroo fertility control. Photo by Ray Drew

Modelling of this approach, based on local population demographic data, indicated the strategy of small, frequent culls to be the most effective

means of maintaining conservation target densities of kangaroos, both operationally, and to limit the number of animals needing to be culled (ACT

Government 2010). As this 'maintenance' mode of kangaroo management was achieved across the reserves already in the programme, further sites could be added without proportional changes in the total resources required for the culling programme each year. This gradual approach ensured management objectives were readily achieved at each site (Fig. 6), and enabled progressive expansion of the conservation culling programme to other priority sites over time.

The science: calculation of the number to cull

Target densities of kangaroos, to achieve conservation objectives, were determined based on an ecological model developed specifically for the Eastern Grey Kangaroo in the temperate environment (Fletcher 2006). The model adopted the same structure as Caughley's (1987) interactive model based on red kangaroos in arid rangelands, which has been used for decades to guide the national commercial harvest of kangaroos and

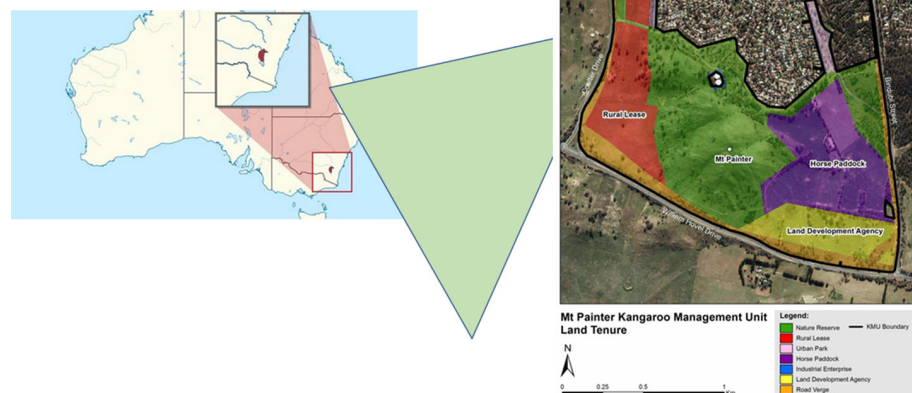


Figure 5. The Mt Painter Kangaroo Management Unit, of 2.08 sq km, is bounded by suburbs and three high-speed roads (≥ 80 km/h) which inhibit kangaroo movements. It comprises several land tenures (semi-transparent colours), all occupied by the same kangaroo population.

Common Wallaroo (Pople *et al.* 2010, 2018). As such, it incorporated local estimates of the pasture response (pasture growth rate as a function of weather and herbage mass), kangaroo numerical response (population growth in relation to pasture availability), and kangaroo functional response (food consumption rate as a function of pasture availability). Unlike Caughley's original model, the eastern grey kangaroo version considered the availability of green (living) herbage mass (rather than total herbage mass) and recognised the seasonality of temperate grasslands by incorporating monthly temperature and rainfall values from local weather stations (Fletcher 2006). Pasture and kangaroo numerical response rates were estimated using weather stations, exclosure cages and kangaroo counts at three sites in and near the ACT, and the functional response was estimated using three purpose-built 'graze-down' pens in each of two pasture types (Fletcher 2006).

Model output (Table 2) simulated five management options: no reduction in kangaroo density; a commercial culling type approach (~20 per

cent); winter culling to a mean density of approximately 1.0 kangaroo/ha; winter culling to approximately 1.6 kangaroo/ha; and culling to a density considered consistent with achieving economic gains on rural land. Fig. 7 shows the effect of the five management options on kangaroo and vegetation density. The culling regimes tested in the model showed that reductions greater than those set by a commercial quota (i.e. approximately 20 per cent of population, Pople *et al.* 2018) were required to achieve vegetation responses that enabled the development of tussocky grass structures thought to be associated with conservation of threatened vertebrate species (e.g. Striped Legless Lizard, *Delma impar*, Howland *et al.* 2016b). Culling to a mean density of approximately 1.0 kangaroo/ha resulted in increased herbage mass, yet still retained large numbers of kangaroos in the grassland ecosystem (Table 2, Fig. 7). It is interesting to note that contrary to intuition, high levels of kangaroo culling may not be associated with increased herbage mass where removals are insufficient to exceed ecological thresholds. For

example, the removal of 800 kangaroos (0.5 kangaroos/ha) from Goo-gong Nature Reserve was ineffective in meeting the stated objectives of increased herbage mass, and reduced soil erosion and associated water contamination in 2004, due to the compensatory influences of increased juvenile survival (ACT Government 2010, p. 37).

In order to apply the general 'grassland' target density of 1.0 kangaroo/ha to KMUs comprising a mix of vegetation communities, this target density was adjusted for the negative effect of tree cover on herbage mass by making the target density for other vegetation structures inversely proportional to tree cover, that is 0.9/ha in Open Woodland, 0.5/ha in Woodland and 0.1/ha in Open Forest and Forest. To enable this adjustment to be applied, a vegetation map was prepared, by satellite image analysis, to provide consistent vegetation data for the full area of all KMUs (Wimpenny *et al.* 2015). As the proportions of each class of woody vegetation differ between KMUs, no two KMUs have the same overall target kangaroo density. Additional KMu-specific adjustments, based on expert judgement, were applied to this base formula in relation to factors such as strategic livestock grazing (e.g. for fire fuel management) or priority conservation values (e.g. the habitat preference of local threatened species; Fig. 8).

A key element of calculating numbers to cull is establishing the current kangaroo population density within a KMu. Each year from 2009, surveys were conducted to estimate kangaroo density across each KMu being considered for culling. Three counting methods, in order of preference and increasing cost, were used: Total Count, Walked Line Transect Count or Faecal Pellet Count (for details of methods see ACT Government 2010). A trial, on five sites in 2014, showed that the results of the different count methods were not

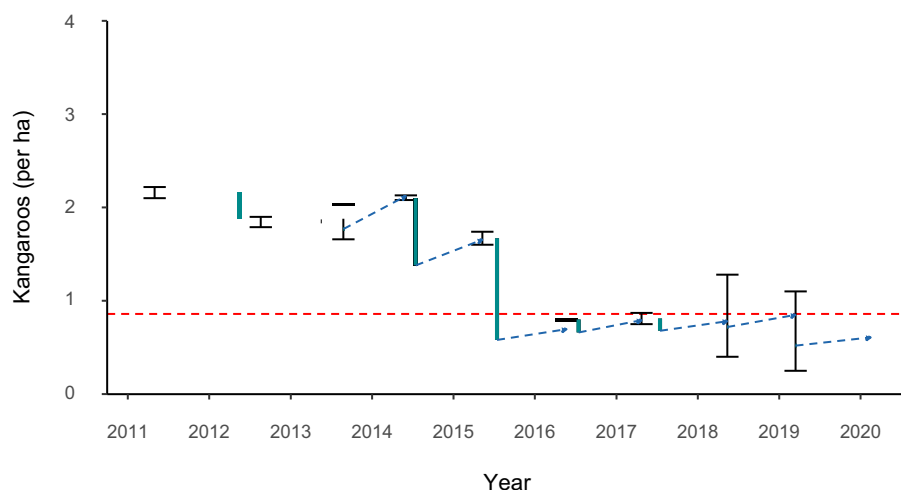


Figure 6. Change in kangaroo density over time at a representative culled site (The Pinnacle Nature Reserve) over time (black circles; average + minimum and maximum sweep counts 2011–2017; mean + 95% confidence interval for walked line transect counts 2018–2019). Annual culls (vertical green bar) are initially large to reduce the population to the target density (horizontal red dashed line), with smaller ‘maintenance’ culls undertaken as needed thereafter to maintain sustainable densities. Blue dotted arrows indicate predicted post-cull population growth between years.

significantly different, and no method produced consistently higher or lower results than the others (ACT Government unpublished data). The target density was deemed to be the average across the year (i.e. the population will start below, and end higher, than the nominated target density). Late autumn and early winter (i.e. April to June) were the preferred seasons to count kangaroos in the ACT, because this is a time of brief stability in the annual cycle of kangaroo populations (Snape *et al.* 2021 this issue). However, the overlap in timing with the delivery of the operational components of the culling programme presented both logistical hurdles and meant that population estimates calculated around 12 months prior to management decisions being made.

As well as conservation considerations, operational factors, including terrain, vehicular access, and public safety, influenced culling priorities. Experimental densities of kangaroos were applied in two areas of Canberra Nature Park to further inform grazing impacts on biodiversity and woodland restoration processes as part of the Mulligans Flat-Goorooyarroo Wood-

land Experiment (www.mfgowoodlandexperiment.org.au).

The future: an integrated approach within an adaptive management framework

Shift from kangaroo density to density relative to grassland condition

Biodiversity in grassy ecosystems is linked directly to the ground-layer vegetation, rather than to kangaroo density *per se* (Howland *et al.* 2014; Snape *et al.* 2018). Therefore, a major recommendation of the 2018 Kangaroo Management Research Workshop was to shift the focus of the conservation culling programme from one of maintaining ‘grassland conservation densities’ of kangaroos towards one more focused on the direct and integrated management of the grassy vegetation layer (Gordon & Snape, 2019). Whilst the objective of kangaroo management to date has been to avoid biodiversity loss resulting from excessive pasture depletion (ACT Government 2010), the detrimental impacts of excessive herbage mass on

biodiversity have also been recognised within key conservation areas within Canberra Nature Park. Here, exclusion fencing or areas of exotic pasture species have resulted in a build-up of tall rank herbage that is avoided by kangaroos. In these cases, relying on the utilisation of rank pastures by resident herbivores was found to be an ineffective approach to reducing excess herbage which instead resulted in significant impacts of heavy grazing on adjacent areas of shorter (more preferred) grass. In this instance, the integrated use of livestock grazing and patch burning were used successfully to remove excess herbage and restore conditions favourable to grazing by kangaroos, such that the ongoing maintenance of appropriate grass structures in these areas might be achieved once again by native herbivores.

The observation of decreased herbivory under higher herbage mass conditions presumably because there are structural (e.g. stems) and compositional (dead vs live leaf) components in high-biomass swards (c.f., Benvenuti *et al.* 2008 for cattle), which, once accumulated, are retained within grassy ecosystems, even at

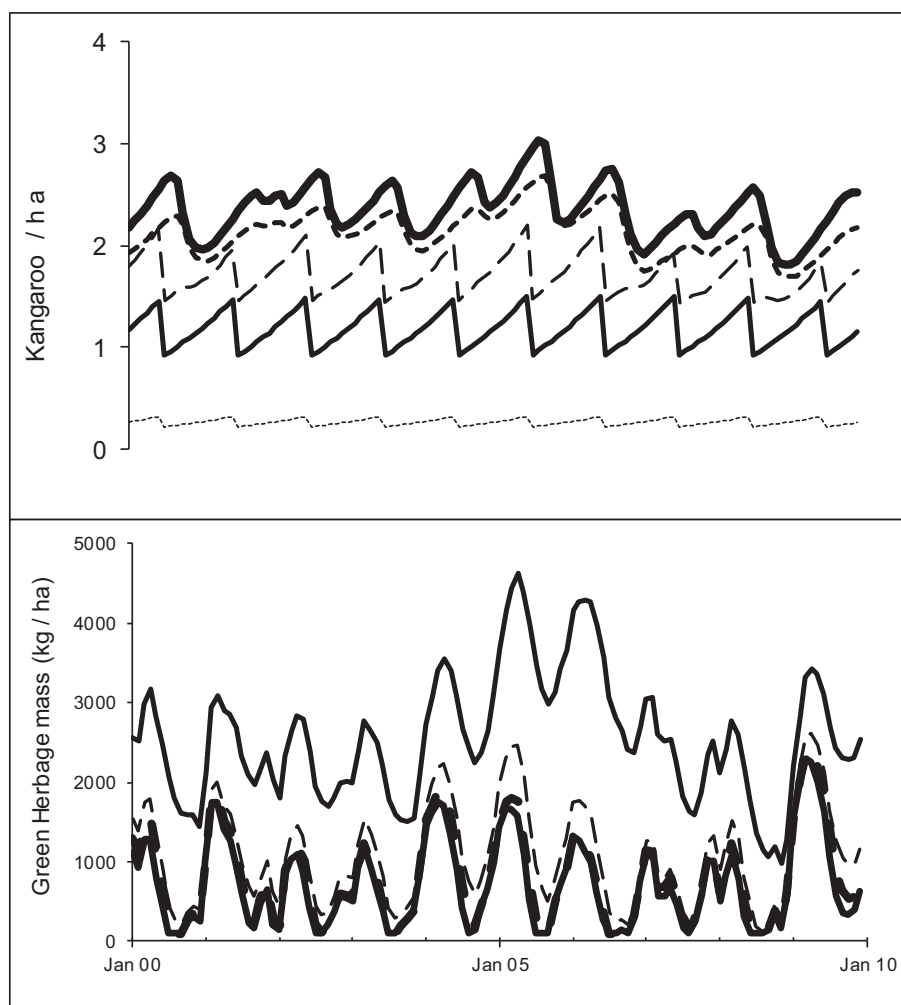


Figure 7. Example of graphical output from kangaroo–pasture model (Fletcher 2006) for a 10-year period. Upper chart, kangaroo density; lower chart, green herbage mass at the same time. Dates are for hypothetical years with the typical variation in the monthly temperature and rainfall of Canberra, ACT, and Queanbeyan, NSW. Five possible management scenarios are illustrated: unmanaged kangaroos, bold continuous line; hypothetical lighter conservation cull, long dashes; kangaroo cull in nature conservation reserves, fine continuous line; typical ACT rural kangaroo management, fine dotted line. See text for further explanation.

high kangaroo densities (> 4 kangaroos/ha). Previous studies of the functional responses of red and western grey kangaroos in chenopod shrublands (Short, 1987), and of eastern grey kangaroos in temperate grasslands (Fletcher 2006), have also demonstrated a benefit of using real-time data on grassy layer biomass to improve estimations of per capita off-take.

To address these issues, the preferred approach identified in the Kangaroo Management Research Workshop towards managing the grassy layer was to determine a ‘safe

operating environment’ (adapted from Rockström *et al.*, 2009) for key characteristics known to influence biodiversity responses, such as grass height, percentage of bare ground and thatch depth (Howland *et al.* 2014, 2016a; Smith *et al.* 2018; Snape *et al.* 2018). The Workshop also identified that detailed mapping of key grass communities within reserves, coupled with annual monitoring of grassy layer structure, and modelling of anticipated pasture growth rates at the management polygon scale, would provide an improved basis for managing the impacts of kangaroo

grazing as part of an integrated approach to protecting conservation values.

Local research suggests that the greatest biodiversity benefits occur at an average grass height of between approximately 5 and 12 cm (Howland *et al.* 2014, 2016a; Smith *et al.* 2018; Snape *et al.* 2018) although specific ‘safe operating environments’ are likely to vary amongst grassy communities and/or reserves depending on individual priority biodiversity values. A heterogeneous grass layer (e.g. high variation in grass heights) is known to provide habitat for legless lizards

Table 2. Outcome of five modelled kangaroo management scenarios. See text for explanation

	Unmanaged	Commercial harvest	Nature Conservation Reserve cull	Hypothetical conservation cull for higher kangaroo density	Typical ACT Commercial Grazing Property
Mean annual rainfall (mm)	616	616	616	616	616
95% confidence interval	24	24	24	24	24
Mean no. kangaroos shot/sq.km./year	0	29	136	154	206
95% confidence interval		14	6	12	1
Mean no. kangaroos remaining/sq.km./year	223	197	110	162	41
95% confidence interval	115	99	47	74	12
Mean green herbage density (kg/ha)	671	791	2013	1087	3563
95% confidence interval	90	135	651	303	1027
Mean green herbage eaten (kg/ha/year)	5005	4785	3978	4609	1638
95% confidence interval	1482	1645	1450	1729	444
Mean green herbage gained (kg/ha)	0	120	1342	416	2891

**Figure 8.** The Canberra Grassland Earless Dragon (*Tympanocryptus lineata*) is one of eighteen threatened species dependent on the fragmented grassy habitat within Canberra Nature Park. Photo by Melissa Snape.

(Brown *et al.* 2011; Howland *et al.* 2016b) and increase native plant diversity (Smith *et al.* 2018). The importance of promoting heterogeneity of grass structure is consistently emphasised as being key to grassland management globally (Vickery *et al.*

2001; Fuhlendorf *et al.* 2006; Pöyry *et al.*, 2006). At the landscape level, maintaining some areas where herbage mass exceeds this 'safe operating environment' may also contribute positively to a heterogeneous grassy layer, especially where they persist to provide refugia during periods of drought (Howland *et al.* 2014). At the local patch level, preventing more than 30 per cent of the patch becoming short is recommended for native pasture in south-eastern Australia (McIntyre & Tongway, 2005).

Monitoring grassy layer condition

In implementing the Workshop's recommendations, management polygons were mapped across Canberra Nature Park in the 2018–2019 summer to reflect variations in grassy layer composition, and hence inherent structural attributes and appropriate use of management tools. Annual monitoring of these polygons will inform the calculation of target kangaroo densities, based on grassy layer condition within individual KMUs, providing a surrogate for effective threatened species habitat, and an

evidence base for the strategic and integrated use of other herbage mass management tools such as fire (e.g. Driscoll *et al.* 2010), slashing (e.g. Smith *et al.* 2018), livestock grazing (e.g. McIntyre & Tongway, 2005; Mavromihalis *et al.* 2013), and the installation of structures to exclude grazing such as placement of coarse woody debris, surface rock or fences (e.g. Manning *et al.* 2013; McDougall *et al.* 2016). Monitoring will include on ground and quadrat-based assessments of grass height and cover, as well as other information relevant to informing management decisions including dominant grass type, percentage of bare ground, and depth and cover of grass thatch. This approach will enable land managers to meet conservation aims at multiple scales, including within the broader KMU at which kangaroo management occurs (Gordon & Snape, 2019). Interventions are now in place, based upon existing scientific knowledge (where available), the system is monitored for its responses to those interventions, and the resulting information is used to update ecological models and future management

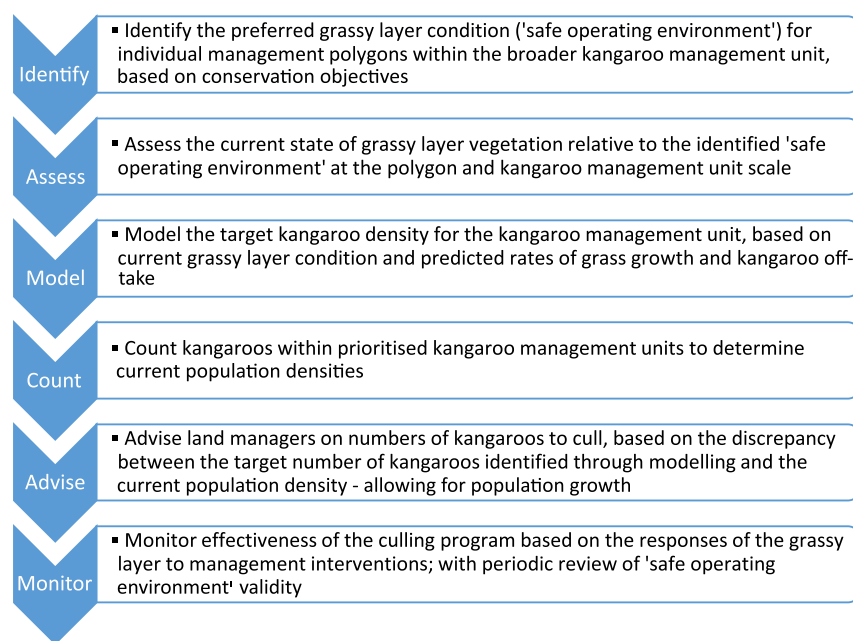


Figure 9. The six recommended steps for adaptive management of kangaroo populations to achieve conservation outcomes.

recommendations (Morgan *et al.*, 2018; see also Gordon 2009).

With weather being the primary driver of grassy ecosystem processes, long-term weather forecasts will be important to predict future pasture growth. Improved weather forecasting information may be available from the Bureau of Meteorology (Bureau of Meteorology 2019); however, it is important to include uncertainty in the herbage growth predictions. Models already exist that could be adapted to provide seasonal and yearly predictions of vegetation production in the Nature Reserves (e.g. Moore *et al.* 1997; Hill *et al.* 2004). However, the predictions from these models would have to be tested with local data.

Current methods for estimating populations

Other recent adjustments to the kangaroo programme include more frequent evaluations of the geographic extent of KMUs, based on evidence of kangaroo population stability and predictability between annual counts, a shift in the timing of kangaroo counts from autumn to summer and the development of a simple model for estimating annual

population growth rates from population density within each KMU (ACT Government 2018). It is predicted that the benefits of having more up to date density estimates when determining annual culling numbers will outweigh any disadvantage of estimating abundance when populations are unstable due to a high number of young emerging from the pouch (Fletcher 2006). The drivers of population dynamics likely deserve further attention in the ACT as research indicates that food availability, rather than population density *per se*, might be a stronger predictor of juvenile recruitment, adult survival and overall rates of annual population change (Portas & Snape, 2018; Festa-Bianchet in Gordon & Snape, 2019). Understanding the anticipated responses of culled populations to management, either in terms of increased immigration, emigration, juvenile recruitment, or mortality (e.g. roadkill), will have a profound influence over the overall effectiveness of reducing abundance below an ecological threshold, and so should continue to be addressed as a priority in this and future wildlife management programmes.

Recommendations

Taken together, the review of current practices and recent research presented at the Kangaroo Management Research Workshop (Gordon & Snape, 2019) recommended steps to setting culling targets that are shown in Fig. 9.

In addition to this recommended approach, the Workshop identified the need to consider a mechanism for identifying priority actions at the landscape scale within the context of environmental risk. For example, management decisions may prioritise mitigating risk at the lower grass height threshold of the safe operating environment (e.g. to avoid loss of species and soil through erosion) rather than focus on areas where excessive herbage mass may also threaten conservation values. However, these decisions will have to consider site-specific conservation values in addition to operational and budgetary constraints. Finally, the monitoring protocols used to inform this adaptive management framework, and the validity of using grassy layer structure as a surrogate for biodiversity, need to be reviewed at appropriate (e.g. five yearly) intervals.

Concluding Remarks

In this paper, we have reviewed the history of the kangaroo management programme in conservation reserves of the ACT, described the current conservation management policy enacted by the ACT Government, and provided recommendations for the future management of kangaroos, and total grazing pressure, in the ACT's nature reserves. Left unchecked, kangaroo grazing can have adverse impacts on the conservation values of grassy ecosystems. Recent research has demonstrated the importance of vegetation structure and composition for a range of native temperate grassy ecosystem taxa within the Australian Capital Territory (ACT), as well as specific grassy habitat requirements for species of conservation concern. Extensive research and modelling have identified approximately 1 kangaroo/ha to be appropriate to achieve biodiversity conservation objectives in these grassy ecosystems. Within the ACT, kangaroo densities are assessed and managed to meet these conservation objectives across multi-tenure land-holdings within a kangaroo management unit (KMU).

The approach taken to conservation culls of the Eastern Grey Kangaroo in the ACT is likely of broad relevance to management of overabundant native wildlife elsewhere in peri-urban Australia, in terms of policy development, community responses, and the nature of the scientific evidence upon which such programmes would likely depend. The broader implications of the management approach for kangaroos in the ACT are the need for government agencies to work in collaboration with stakeholders across civil society to ensure a social licence to operate. Key to achieving conservation aims is the transition from a cull focused on density reduction to one that sets key performance indicators based upon the conservation goals. As with many other circumstances, the

evidence base for these management actions in the ACT has grown over time, and so an adaptive management approach of plan, act, monitor and review will allow for further evidence to be brought to bear in future decision-making. Kangaroo management in the ACT demonstrates this cycle in action, and is a good model for macropod management across the Australian states and territories and wildlife management more generally across the globe.

Acknowledgements

We would like to thank the ACT Government for supporting the Kangaroo Management Research Workshop held in August 2018. We also thank the participants, not named as authors, for their contribution to making the workshop a success. Note that MS, BH, CW and GB declare a conflict of interest as employees of the ACT Government. Iain Gordon is additionally affiliated with the James Hutton Institute (Aberdeen, AB15 8QH, UK), Central Queensland University (Townsville, Queensland, Australia) and Land & Water (CSIRO, Townsville, Queensland, Australia), and Sue McIntyre is additionally affiliated with Land and Water (CSIRO, Canberra, ACT, Australia). This paper is part of the special issue 'Optimum management of overabundant macropods' published in *Ecological Management & Restoration*.

References

- 360 Degree Films. (2011) Kangaroo Mob. [Accessed 30 Sept 1996.] Available from URL: <https://360degreefilms.com.au/productions/kangaroo-mob>.
- ACAT (2009) ACT civil and administrative tribunal decisions: animal liberation NSW vs conservator of flora and fauna. [Accessed 30 Sept 1996.] Available from URL: <http://acat.act.gov.au/decisions/animal-liberation-v-conservator-of2>.
- ACAT (2014) ACT civil and administrative tribunal decisions: animal liberation ACT vs conservator of flora and fauna. [Accessed 30 Sept 1996.] Available from URL: <http://acat.act.gov.au/decisions/animal-liberation-act-v-conservator>.

- ACT Government (2010) *ACT Kangaroo Management Plan*. ACT Government, Canberra, Australia. [Accessed 30 Sept 1996.] Available from URL: http://www.environment.act.gov.au/_data/assets/pdf_file/0020/902423/Kangaroo_Management_Plan_complete_for_web.pdf.
- ACT Government (2017) *Eastern Grey Kangaroo: Controlled Native Species Management Plan*. ACT Government, Canberra, Australia.
- ACT Government (2018) Eastern grey kangaroo. Conservation culling advice 2018. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/_data/assets/pdf_file/0016/1242610/Cull-Recommendations-Report-UPDATE-180827-Web-Accessible-Pdf2.pdf.
- ACT Government (2019a) *Canberra Nature Park*. Draft Reserve Management Plan, Environment, Planning and Sustainable Development Directorate, ACT Government, Canberra, Australia.
- ACT Government (2019b) 2019 Kangaroo Cull. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/parks-conservation/plants-and-animals/urban_wildlife/local_wildlife/kangaroos/2019-kangaroo-cull.
- Augustine D. J. and McNaughton S. J. (1998) Ungulate effects on the functional species composition of plant communities: Herbivore selectivity and plant tolerance. *Journal of Wildlife Management* **62**, 1165–1183.
- Augustine D. J., McNaughton S. J. and Frank D. A. (2003) Feedbacks between soil nutrients and large herbivores in a managed savanna ecosystem. *Ecological Applications* **13**, 1325–1337.
- Ballard G. (2008) Peri-urban kangaroos. Wanted? Dead or alive. In: *Too Close for Comfort: Contentious Issues in Human-Wildlife Encounters* (eds D. Lunney, A. Munn and W. Meikle). pp. 49–51. Royal Zoological Society of New South Wales, Sydney.
- Barton P. S., Cunningham S. A., Macdonald B. C. T., McIntyre S., Lindenmayer D. B. and Manning A. D. (2013) Species traits predict assemblage dynamics at ephemeral resource patches created by carrion. *PLoS One* **8**, e53961.
- Barton P. S., Manning A. D., Gibb H., Wood J. T., Lindenmayer D. B. and Cunningham S. A. (2011) Reduction of native vertebrate grazing and addition of logs benefit beetle diversity at multiple scales. *Journal of Applied Ecology* **48**, 943–951.
- Ben-Ami D. and Mjadwesch R. (2017) Integrating animal protection criteria into conservation management: a case study of the management of Eastern Grey Kangaroos in the ACT. *Israel Journal of Ecology and Evolution* **63**, 23–33.
- Benvenuti M. A., Gordon I. J. and Poppi D. P. (2008) The effects of stem density of tropical swards and age of grazing cattle on their foraging behaviour. *Grass and Forage Science* **63**, 1–8.
- Brown G. W., Dorrough J. W. and Ramsey D. S. (2011) Landscape and local influences on patterns of reptile occurrence in grazed

- temperate woodlands of southern Australia. *Landscape and Urban Planning* **103**, 277–288.
- Bureau of Meteorology (2019) Climate Outlooks –Weeks, Months and Seasons. [Accessed 30 Sept 1996.] Available from URL: <http://www.bom.gov.au/climate/outlooks/#/rainfall/median/weekly/0>.
- Canberra Times (2014a) Letters to the Editor published on 24/6/2014, letter by Lara Drew. [Accessed 30 Sept 1996.] Available from URL: <https://www.canberratimes.com.au/story/6142428/tax-to-hit-contractors>.
- Canberra Times (2014b) Letters to the Editor published on 27/6/2014, letter by Frankie Seymour. [Accessed 30 Sept 1996.] Available from URL: <https://www.canberratimes.com.au/story/6142413/no-one-is-above-law>.
- Caughley G. (1987) Ecological relationships. In: *Kangaroos: Their Ecology and Management in the Sheep Rangelands of Australia* (eds G. Caughley, N. Shepherd and J. Short), pp. 159–187. Cambridge University Press, Cambridge, UK.
- Coulson G. (2001) Overabundant kangaroo populations in southeastern Australia. In: *Wildlife, Land and People: Priorities for the 21st Century. Proceedings of the Second International Wildlife Management Congress* (eds R. Field, R. J. Warren, H. Okarma and P. R. Sievert) pp. 238–242. The Wildlife Society, Bethesda, USA.
- Coulson G. (2006) Exploding kangaroos: assessing problems and setting targets. In: *Pest or Guest: the Zoology of Overabundance* (eds D. Lunney, P. Eby, P. Hutchings and S. Burgin), pp. 174–181. Royal Zoological Society of New South Wales, Sydney, Australia.
- Driscoll D. A., Lindenmayer D. B., Bennett A. F. *et al.* (2010) Fire management for biodiversity conservation: key research questions and our capacity to answer them. *Biological Conservation* **143**, 1928–1939.
- Fletcher D. (2006) Population Dynamics of Eastern Grey Kangaroos in Temperate Grasslands. PhD thesis. Institute for Applied Ecology. University of Canberra, Canberra, Australia.
- Fletcher D. (2007) Managing eastern grey kangaroos *Macropus giganteus*. In: *Pest or Guest: the Zoology of Overabundance* (eds D. Lunney, P. Eby, P. Hutchings and S. Burgin), pp. 117–128. Royal Zoological Society of New South Wales, Sydney, Australia.
- Francis A. (2012) Scientists threatened by vandals. Media report by. [Accessed 30 Sept 1996.] Available from URL: <https://www.abc.net.au/news/2012-06-05/bettong-conservation-under-threat/4053358>.
- Fuhlendorf S. D., Harrell W. C., Engle D. M., Hamilton R. G., Davis C. A. and Leslie D. M. Jr (2006) Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. *Ecological Applications* **16**, 1706–1716.
- Fynn R. W. S., Augustine D. J., Peel M. J. S. and de Garine-Wichatitsky M. (2016) Strategic management of livestock to improve biodiversity conservation in African Savannahs: A conceptual basis for wildlife-livestock co-existence. *Journal of Applied Ecology* **53**, 388–397.
- Gordon I. J. (2009) What can Australia learn from deer management overseas? In: *Proceedings of the National Feral Deer Management Workshop*. (ed S. McLeod) pp. 78–83. Invasive Animals Cooperative Research Centre, Canberra, Australia.
- Gordon I. J. and Prins H. H. T. (eds.) (2019) *The Ecology of Grazing and Browsing II*. Springer, New York, USA.
- Gordon I. J. and Snape M. (2019) Kangaroo Management Research Workshop. Summary Report. ACT Government, Canberra, Australia. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/_data/assets/pdf_file/0006/1550292/kangaroo-management-research-report-april-2019.pdf.
- Hill M. J., Donald G. E., Hyder M. W., and Smith R. C. G. (2004) Estimation of pasture growth rate in the south west of Western Australia from AVHRR NDVI and climate data. *Remote Sensing of Environment* **93**, 528–545.
- Howland B. W., Gordon I. J., Manning A. D., Stojanovic D. and Lindenmayer D. B. (2014) Eaten out of house and home: impacts of high intensity grazing by an ecosystem engineer on ground-dwelling reptiles. *PLoS One* **9**, e105966. <https://doi.org/10.1371/journal.pone.0105966>.
- Howland B. W., Stojanovic D., Gordon I. J. *et al.* (2016b) Habitat preference of the striped legless lizard: implications of grazing by native herbivores and livestock for conservation of grassland biota. *Austral Ecology* **41**, 455–464.
- Howland B. W., Stojanovic D., Gordon I. J., Radford J., Manning A. D. and Lindenmayer D. B. (2016a) Birds of a feather flock together: using trait-groups to understand the effect of macropod grazing on birds in grassy habitats. *Biological Conservation* **194**, 89–99.
- Johnson C. (2015) An ecological view of the dingo. In: *The Dingo Debate, Origins, Behaviour and Conservation* (ed B. Smith), pp. 191–214. CSIRO Publishing, Melbourne, Australia.
- Manning A., Cunningham R. and Lindenmayer D. (2013) Bringing forward the benefits of coarse woody debris in ecosystem recovery under different levels of grazing and vegetation density. *Biological Conservation* **157**, 204–214.
- Mavromihalis J. A., Dorrrough J., Clark S. G., Turner V. and Moxham C. (2013) Manipulating livestock grazing to enhance native plant diversity and cover in native grasslands. *The Rangeland Journal* **35**, 95–108.
- McDougall A., Milner R. N. C., Driscoll D. A. and Smith A. L. (2016) Restoration rocks: integrating abiotic and biotic habitat restoration to conserve threatened species and reduce fire fuel load. *Biodiversity and Conservation* **25**, 1529–1542.
- McIntyre S., Nicholls A. O., Graff P. and Stol J. (2018) Experimental reintroduction of three grassland forbs to assess climate-adjusted provenancing, grazing protection and weed control. *Australian Journal of Botany* **66**, 628–639.
- McIntyre S., Nicholls A. O. and Manning A. D. (2017) Trajectories of floristic change in grassland: landscape, land use legacy and seasonal conditions overshadow restoration actions. *Applied Vegetation Science* **20**, 582–93.
- McIntyre S., Stol-Harvey J., Nicholls A. O., Campbell M., Reid A., Manning A., and Lindenmayer D. (2010) Biomass and floristic patterns in the ground layer vegetation of box-gum grassy eucalypt woodland in Goorooyarroo and Mulligans Flat Nature Reserves, Australian Capital Territory. *Cunninghamia* **11**, 319–357.
- McIntyre S. and Tongway D. (2005) Grassland structure in native pastures: links to soil surface condition. *Ecological Management & Restoration* **6**, 43–50.
- Micromex Research (2008) Attitudes of ACT Residents towards Kangaroos and Kangaroo Management – Resident Research. A research report prepared for the ACT Government (Parks, Conservation and Lands, Territory and Municipal Services). Micromex, Wyong North, NSW, Australia. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/parks-conservation/plants-and-animals/urban_wildlife/local_wildlife/kangaroos/kangaroo_mgt_opinion_poll.
- Micromex Research (2012) Attitudes of ACT Residents towards Kangaroos and Kangaroo Management: Community Survey. Micromex, Wyong North, NSW, Australia. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/parks-conservation/plants-and-animals/urban_wildlife/local_wildlife/kangaroos/kangaroo_mgt_opinion_poll.
- Micromex Research (2015) ACT Government - Attitudes of ACT Residents towards Kangaroos and Kangaroo Management. Micromex, Wyong North, NSW, Australia. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/parks-conservation/plants-and-animals/urban_wildlife/local_wildlife/kangaroos/kangaroo_mgt_opinion_poll.
- Moore A. D., Donnelly J. R. and Freer M. (1997) GRAZPLAN: Decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels, and the GrassGro DSS. *Agricultural Systems* **55**, 535–582.
- Morgan J., Wright J., Whelan J. *et al.* (2018) What does it take to do successful adaptive management? A case study highlighting Coastal Grassy Woodland restoration at Yanakie Isthmus. *Ecological Management & Restoration* **19**, 111–123.
- Neave H. M. and Tanton M. T. (1989) The effects of grazing by kangaroos and rabbits on the vegetation and the habitat of other fauna in the Tidbinbilla Nature Reserve, Australian Capital Territory. *Australian Wildlife Research* **16**, 337–351.
- Owen-Smith N. (2002) *Adaptive Herbivore Ecology*. Cambridge University Press, Cambridge, UK.
- Pople A., Gentle M. and Brennan M. (2018) Achieving pest control through sustainable wildlife use. In: *Advances in Conservation through Sustainable Use of Wildlife* (eds G. Baxter, N. Finch and P. Murray), pp. 151–162. The University of Queensland, Brisbane, Australia.
- Pople A., Grigg G., Phinn S., Menke N., McAlpine C. and Possingham H. (2010) Reassessing spatial and temporal dynamics of kangaroo populations. In: *Macropods: The Biology of Kangaroos, Wallabies and Rat-kangaroos*

- (eds G. Coulson and M. D. B. Eldridge), pp. 197–210. CSIRO Publishing, Melbourne, Australia.
- Portas T. J. and Snape M. A. (2018) *Factors Influencing Sub-adult Mortality Events in Eastern Grey Kangaroos (Macropus giganteus) in the ACT*. Environment, Planning and Sustainable Development Directorate, ACT Government, Canberra, Australia.
- Pöyry J., Luoto M., Paukkunen J., Pykälä J., Rautikainen K. and Kuussaari M. (2006) Different responses of plants and herbivore insects to a gradient of vegetation height: an indicator of the vertebrate grazing intensity and successional age. *Oikos* **115**, 401–412.
- Prowse T. A., Johnson C. N., Cassey P., Bradshaw C. J. A. and Brook B. W. (2014) Ecological and economic benefits to cattle rangelands of restoring an apex predator. *Journal of Applied Ecology* **52**, 455–466.
- Pulsford S. and Snape M. A. (2019) Kangaroo management on a localised scale: an evaluation of effectiveness. Unpublished report. Environment, Planning and Sustainable Development Directorate, ACT Government, Canberra, Australia.
- Ramp D. and Roger E. (2008) Frequency of animal-vehicle collisions in NSW. In *Too close for comfort: contentious issues in human-wildlife encounters* (eds D. Lunney, A. Munn and W. Meikle), pp. 118–126. Royal Zoological Society of New South Wales, Mosman, NSW, Australia.
- RiotACT The (2012) Rolling nature park vandalism as cull protest. [Accessed 30 Sept 1996.] Available from URL: <https://the-riotact.com/rolling-nature-park-vandalism-as-cull-protest/74518>.
- Ripple W. J. and Beschta R. L. (2004) Wolves and the ecology of fear: can predation risk structure ecosystems. *BioScience* **54**, 755–766.
- Ripple W. J., Estes J. A., Beschta R. L. *et al.* (2014) Status and ecological effects of the world's largest carnivores. *Science* **343**, 1241484.
- Ritchie E. G., Elmhagen B., Glen A. S., Letnic M., Ludwig G. and McDonald R. A. (2012) Ecosystem restoration with teeth: what role for predators? *Trends in Ecology & Evolution* **27**, 265–271.
- Robertshaw J. D. and Harden R. H. (1989) Predation in Macropodidae: a review. In: *Kangaroos, Wallabies and Rat-Kangaroos* (eds G. C. Grigg, P. J. Jarman and I. Hume), pp. 735–753. Surrey Beatty, Sydney, Australia.
- Rockström J., Steffen W., Noone K. *et al.* (2009) A safe operating space for humanity. *Nature* **461**, 472–475.
- Sharp T. (2012) Factors influencing public perceptions of kangaroo management. [Accessed 30 Sept 1996.] Available from URL: <https://www.rspca.org.au/sites/default/files/web-site/The-facts/For-students/Scholarships/Past-scholarships/Sharp.pdf>.
- Short J. (1987) Factors affecting food intake of rangelands herbivores. In: *Kangaroos: Their Ecology and Management in the Sheep Rangelands of Australia* (eds G. Caughley, N. Shepherd and J. Short), pp. 84–99. Cambridge University Press, Cambridge.
- Smith A. L., Barrett R. L. and Milner R. N. C. (2018) Annual mowing maintains plant diversity in threatened temperate grasslands. *Applied Vegetation Science* **21**, 207–218.
- Snape M., Caley P., Baines G. and Fletcher D. (2018) Kangaroos and conservation. Assessing the effects of kangaroo grazing in lowland grassy ecosystems. Environment, Planning and Sustainable Development Directorate, ACT Government, Canberra. [Accessed 30 Sept 1996.] Available from URL: https://www.environment.act.gov.au/_data/assets/pdf_file/0004/1195078/Tech-Report_-Kangaroos-and-Conservation_-Web-Accessible-2.pdf.
- Tolfts R. (2019). Do eastern grey kangaroos (*Macropus giganteus*) use biological corridors when displaced by development? Honours Thesis, Australian National University.
- Vickery J. A., Tallowin J. R., Feber R. E. *et al.* (2001) The management of lowland neutral grasslands in Britain: effects of agricultural practices on birds and their food resources. *Journal of Applied Ecology* **38**, 647–664.
- Viggers K. (2015) *The Grass Castle*. Allen and Unwin, Sydney, Australia.
- Vivian L. M. and Godfree R. C. (2014) Relationships between vegetation condition and kangaroo density in lowland grassy ecosystems of the northern Australian Capital Territory: analysis of data 2009, 2010 and 2013. CSIRO, Australia.
- Wilson G. R. and Edwards M. (2019) Professional kangaroo population control leads to better animal welfare, conservation outcomes and avoids waste. *Australian Zoologist* **40**, 181–202.
- Wimpenny C., Howland B. and Fletcher D. (2015) A Simple but Useful Map of Vegetation Structure in and Near Canberra. Technical Report 33. Environment and Planning Directorate, ACT Government, Canberra, Australia.