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Low-intensity kangaroo grazing has largely benign effects on soil health

By David J. Eldridge, Jingyi Ding and Samantha K. Travers

Summary ***Kangaroos (Macropus* spp., *Osphranter* sp.) are the most ubiquitous free-ranging herbivores in Australia. Much has been written on their impacts on plant community composition and how they interact with livestock, particularly in extensive rangelands. Little is known, however, about how kangaroos affect soil function and their relationship with healthy soils, nor the impact of peri-urban populations of kangaroos where they might come into conflict with humans. To address this, we used exclosures to examine the impacts of low densities of kangaroos on the morphology of the soil surface in a peri-urban environment on the outskirts of Sydney, Australia. We found that kangaroo grazing was associated with reduced herbaceous biomass and cover, and biocrust cover, and surfaces were generally more stable, had a greater cover and incorporation of litter and had greater plant species richness. There were no differences in indices of nutrient cycling nor stability. Overall, our study supports the notion that kangaroo grazing, at the current low densities experienced in this peri-urban reserve, has had no significant deleterious effect on soil surface health, as measured by the morphology of the surface. We conclude that grazing at the current low levels (~70 km^{-2}) is unlikely to have major long-term negative effects on soil surface condition.**

Key words: *grazing, herbivory, Landscape function analysis, macropod, Macropus* spp., Soil health, soil morphology.

David J. Eldridge *is Professor with the Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales (Sydney, New South Wales 2052, Australia. Email: d.eldridge@unsw.edu.au).* ***Jingyi Ding*** *and* ***Samantha K. Travers*** *are PhD student and Research Associate, respectively, with the Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales (Sydney, New South Wales 2052, Australia Email: jingyi.ding@student.unsw.edu.au; Tel: + 61 2 9385 2194).*

Implications for managers

- Kangaroo grazing reduced herbaceous biomass and cover, but resulted in greater plant species richness.
- Our findings provide only limited evidence that kangaroo grazing at low densities had any significant negative effects on soil health.
- Managers need to be aware of potential longer-term legacy effects of high levels of kangaroo grazing on attributes other than soil surface health.

Introduction

Kangaroos (*Macropus* spp., *Osphranter* sp.) are native herbivores with a widespread distribution across large areas of the continent. Since European colonisation, population densities of the two most common species, the Eastern Grey Kangaroo (*Macropus giganteus*) and the Western Grey Kangaroo (*Macropus fuliginosus*), have increased substantially due to structural changes in the vegetation, addition of more watering points and, potentially, control of top-order predators such as the Dingo (*Canis lupus dingo;* Letnic *et al.*2012). Kangaroos are ubiquitous across Australia, from coastlines to the arid interior (Dawson 1995). Studies of kangaroos using grazing gradients have demonstrated that increased kangaroo densities are associated with reduced germination and establishment of native trees and shrubs (Koch *et al.*2004; Rafferty *et al.*2005), decline in flowering of orchids (Faast & Facelli 2009) and reduced grass biomass (McIntyre *et al.*2015).

Because of their extensive distribution and often large mob sizes, kangaroo activity frequently overlaps with humans. In pastoral environments, they are thought to compete with livestock for grasses and forbs, particularly during droughts (Caughley *et al.*1987) and, in horticultural areas, are often blamed for crop damage. In peri-urban environments, along major highways, rural airfields and defence force reserves, kangaroos often present a hazard for motorists and vehicles (Ramp & Roger 2008). Kangaroo management often involves culling

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populations, which can be quite challenging in populated areas (ACT 2010). Available research indicates evidence for both increases and declines in the density of kangaroo close to urban areas (Brunton *et al.* 2018; Henderson *et al.* 2018). Kangaroo exclusion by fencing has also been used and has been shown to lead to substantial increases in grass seed production and pasture biomass (Rees *et al.* 2017), increase in plant cover and richness of shrubs and grazing-sensitive species (Gowans *et al.* 2010; Driscoll 2017), and reduced grass mortality (Grice & Barchia 1992).

Despite their ubiquity, we know relatively little about the impacts of kangaroos on soils and soil processes, compared with livestock, as most information comes from studies of rural kangaroo populations in areas grazed by other large herbivores. For example, an extensive study across 451 sites in eastern Australia showed that when compared to European livestock, increasing kangaroo grazing had a few small but positive effects on soil functions with a slight relative reduction in soil nitrogen and phosphorus, and an increase in biocrust cover, likely due to associational, rather than causative, effects (Eldridge *et al.* 2017). A few studies, predominantly from rangelands, have reported effects on soil health (Bailey & Alchin 2000) or altered soil chemistry (Price *et al.* 2010; Morris & Letnic 2017) in areas where kangaroos have been excluded.

We examined the impacts of kangaroos on a suite of soil surface measures that are indicative of healthy, functional soils. Our focus was on kangaroo effects in a peri-urban environment dominated by kangaroos, but in the absence of other large herbivores such as wild Deer or livestock. A key challenge in the kangaroo literature is separating kangaroo effects from those of other herbivores, or ascribing effects solely to the presence or absence of kangaroos alone, rather than considering them in a gradient of kangaroo grazing. We used a series of exclosures that were constructed in 2005 to monitor the effects of kangaroo grazing on an Endangered Ecological Community (Cumberland Plain Woodland), specifically to provide information on their likely effects on plant community composition and therefore whether management of high kangaroo densities might be needed. Kangaroos were the main vertebrate herbivores, enabling us to examine their impacts at paired sites in the absence of other herbivores. We expected that there would be few effects of kangaroos on measures of soil health given that kangaroos have coevolved with plants and soils and that they exert a relatively low pressure on the soil (Bennett 1999). Our study is novel because it provides important information on the impacts of kangaroos in conservation areas close to urban settlements and provides insights into their likely impacts on soil health and soil surface condition. There are also few studies of the impacts of kangaroos in urban and peri-urban areas, and none has examined how kangaroos might affect soil or soil surface functional processes.

Methods

The study area

Our study was carried out at Wianamatta Regional Park, the former Australian Defence Industries (ADI) site in St Marys, in the Greater Sydney Area, eastern Australia (−33.7, 150.8). The climate is typically temperate, with mild winters (5–18°C July) and warm-to-hot summers (20–32°C). Annual rainfall at Penrith, about 10 km from the study area, averages about 750 mm, with twice as much rain falling in the six warmer months (November to April). Soils are typical of Shale Plains Woodland (Tozer 2003; Tozer *et al.* 2010) and dominated by Wianamatta Group shales and alluviums with high clay content. The dominant overstorey species are Narrow-leaved Ironbark (*Eucalyptus crebra* F.Muell.), Grey Box (*Eucalyptus moluccana* F.Muell.), Forest Red Gum (*Eucalyptus tereticornis* Sm.) and Red Ironbark (*Eucalyptus fibrosa* F.Muell. NSW Scientific Committee 2009). The shrub layer is comprised mostly of Native Blackthorn (*Bursaria spinosa* Cav.) and common ground stratum species including the grasses Three-awned Speargrass (*Aristida vagans* Cav.), Shot Grass (*Paspalidium distans* (Trin.) Hughes) and Weeping Meadow Grass (*Microlaena stipoides* (Labill.) R.Br.), and forbs such as Kidney Weed (*Dichondra repens* J.R.Forst. & G.Forst.) and Tick-Trefoil (*Desmodium varians* (Labill.) G.Don.).

Prior to 1994, a large number of kangaroos were confined within the fenced ADI site. When much of the grassland within the site was slated for housing in 1994, kangaroos presented considerable management issues due to their high numbers, proximity to infrastructure (roads) and their potential to cause considerable environmental damage to the remaining Cumberland Plain Woodland community after conversion of much of the suitable grassland habitat to housing. A sterilisation programme commenced to reduce the kangaroo population, concurrent with the initiation of studies to examine the ecological impacts of reductions in kangaroo numbers across the site using fenced exclosures.

Our study focussed on eight grazing exclosures (30 m by 30 m) and their paired grazed comparisons, co-located within 50 m within the woodland community. The eight exclosure pairs were separated by distances of about 2 km. Exclosures were constructed of portable steel fencing panels (2.1-m-high by 2.4-m-wide panels) joined together and held in place by heavy concrete plinths. There is no evidence that any of the exclosures used in the study has been breached by kangaroos. Kangaroo densities in 2005 when the exclosures were established were approximately 334 km^{-2}, though they were not distributed evenly across the whole site. Densities in open grassy sites probably approximated 400 km^{-2} and in the woodland and forested areas about 290 km^{-2}. Numbers have declined over the past 10 years due to sterilisation. At the time of this study (January 2020), kangaroos numbered about 480, mainly Eastern Grey Kangaroo (but smaller number of Red Kangaroo (*Osphranter rufus*) across the 698 ha (~70 animals/km^2).

Soil health assessment

Within each exclosure and at each paired grazed site, we established a 20-m transect along which we placed five equidistant 0.25 m^2 quadrats (0.5 by 0.5 m). Within each quadrat, we assessed the status and morphology of 14 soil surface attributes, which are indicative of soil health and function (e.g. Maestre & Puche 2009; Eldridge *et al.*2017; Eldridge *et al.*2019). These features were as follows: (i) surface roughness, that is microtopography; (ii) surface hardness, that is the extent to which the surface resists deformation by erosion; (iii) surface cracking, the degree of cracking in the crust; (iv) crust stability, assessed by examining how soils break down in water; (v) soil surface integrity, that is the cover of the soil that is uneroded; (vi) surface deposited soils, that is the cover of any eroded material deposited on the soil; (vii) biological soil crust cover; (viii) plant foliage cover; (ix) plant basal cover; (x) litter cover; (xi) litter depth; (xii) litter origin, that is whether litter is local or transported from elsewhere; (xiii) the degree of litter incorporation; and (xiv) soil texture (Appendix S1). We also counted the number of kangaroo pellets and rabbit pellets to obtain an idea of grazing intensity; measured plant richness; and measured plant biomass by clipping all non-woody plants rooted within the quadrats. Clipped samples were bagged, dried at 60°C for 48 h, and weighed. Combinations of the soil attributes have been used to calculate three indices of soil health (Appendix S1) that define the capacity of the soil to (i) resist disturbance (stability index), (ii) infiltrate water (infiltration index) and (iii) cycle nutrients (nutrient index; Tongway 1995). The indices are highly correlated with ecosystem functions associated with soils (e.g. Maestre & Puche 2009).

Statistical analyses

We used permutational multivariate analysis of variance (PERMANOVA; Anderson 2014) on a matrix of 16 samples (eight sites x two treatments) by 16 explanatory variables (14 soil surface attributes and two plant attributes; Table 1) to examine potential differences in surface composition between grazed and ungrazed treatments. Our model considered Blocks (n = 8) and Treatment (n = 2) and tested possible grazing effects against the Block and Treatment interaction. Euclidean distance was used as the distance measure for the matrix. Because we detected a significant difference in the spectrum of surface attributes in relation to treatment (grazed *cf.* ungrazed), we tested the degree of association between these attributes and treatment using Indicator Species Analysis (Dufréne & Legendre 1997) with the *indicspecies* package in R (De Cáceres & Legendre, 2009). We then undertook separate univariate analyses of each surface attribute, as well as plant biomass, kangaroo and rabbit dung, and the three derived health indices, using linear models, to test whether they differed with kangaroo grazing, using the same analytical structure as described for PERMANOVA. We tested the average dissimilarity of each of the surface attributes between grazed and ungrazed quadrats.

Results

The composition of soil surface attributes differed between grazed and ungrazed sites (Pseudo-$F_{1,7}$ = 5.50, P (perm) = 0.017). Indicator Species Analysis indicated that two soil variables were significant indicators of grazed sites (greater under grazing): crust stability (indicator value [IV] = 0.75, P = 0.002) and plant richness (IV = 0.74, P = 0.027), whereas four indicators were significant indicators of ungrazed sites (lower under grazing): plant biomass (IV = 0.87[1], P = 0.001), plant foliage cover (IV = 0.87, P = 0.001), plant basal cover (IV = 0.87, P = 0.001) and soil surface roughness (IV = 0.87, P = 0.001). Our univariate analyses largely confirmed these results (Table 1). For example, kangaroo grazing was associated with a soil surface with significantly more cracking, greater cover of litter, but less plant foliage and basal cover, and lower biocrust cover, but had a surface crust that was more stable. The index of soil infiltration was marginally greater under grazing, but there were no effects of grazing on the nutrient or stability indices (Table 1, Fig. 1). We also found that grazed sites were slightly, though significantly, more homogeneous in relation to the terms of the fourteen soil surface attributes, and total above-ground biomass (14.1 ± 7.1%, mean ± SE dissimilarity) than ungrazed sites (22.1 ± 7.1%, paired t-test = −2.51, P = 0.04). The largest effect of kangaroo grazing was to reduce total plant biomass by more than 30% (Fig. 1).

Discussion

Our study demonstrated that kangaroo grazing was associated with two modes of action: first, a reduction in the structural character of sites through reduced plant basal area, foliage cover and grass biomass; and second, an increase in functional measures associated with surface stability, litter cover and incorporation,

Table 1. Mean (±SE) values of 14 soil surface attributes, plus plant richness and biomass, measures of ecosystem health, and grazing intensity of kangaroos and rabbits at grazed and ungrazed sites.

Attribute	Grazed		Ungrazed		P-value
	Mean	SE	Mean	SE	
Soil surface attributes					
Surface resistance	3.1	0.29	3.1	0.35	0.095
Surface roughness	1.2	0.06	1.4	0.08	0.950
Surface cracking	3.5[a]	0.21	2.9[b]	0.28	<0.001
Crust stability	4.0[a]	0.03	3.0[b]	0.28	<0.001
Surface integrity	3.9	0.06	4.0	0.03	0.397
Deposited material	4	0	4.0	0.03	0.347
Biocrust cover (%)	2.4	1.07	4.1	1.57	0.055
Litter cover (%)	68.8[a]	4.31	57.9[b]	3.88	0.010
Litter origin	1.5	0	1.5	0	1.000
Litter incorporation	1.3	0.25	1.0	0.02	0.296
Litter depth (mm)	15.8	1.46	16.6	1.40	0.706
Soil texture	2	0.00	2	0.00	1.000
Plants					
Plant foliage cover (%)*	12.5[a]	1.76	34.3[b]	4.16	<0.001
Plant basal cover (%)*	1.1[a]	0.03	1.8[b]	0.14	<0.001
Plant richness	3.4[a]	0.16	2.8[b]	0.17	0.002
Plant biomass (t/ha)	0.4[a]	0.03	1.3[b]	0.21	<0.001
Soil health indices					
Stability index (%)	64.0	0.77	63.3	1.87	0.320
Infiltration index (%)	23.3[a]	0.82	22.4[b]	0.44	0.039
Nutrient index (%)	26.3	3.67	24.0	0.62	0.521
Grazing indicators					
Kangaroo dung (kg/ha)	4.4[a]	0.84	0.2[b]	0.21[†]	0.004
Rabbit dung (kg/ha)	0.02	0.00	0.02	0.00	1.000

*Components of soil surface condition assessment.
[†]Recent incursion by kangaroos due to broken fence.

and plant richness (Fig. 1). Reductions in grass biomass are consistent with studies of kangaroo effects from a range of environments. For example, kangaroos are known to prefer productive, grass-dominated pastures in open habitats (McAlpine *et al.* 1999) and semi-arid floodplains (Iles *et al.* 2010). In temperate grasslands in southern NSW, grazing by kangaroos is known to reduce grass structural complexity (Howland *et al.* 2014) and exclosure studies in northern NSW found significant increases in plant height under kangaroo exclusion (Hunter & Hunter 2019). Longitudinal studies since 2005 at our study site demonstrate that declining kangaroo densities over time are associated with taller groundstorey plants (Robertson 2017), consistent with our observations. We also found that kangaroos reduced grass density and, in some plots, the frequency of very large individual plants (Samantha Travers, unpublished data, 2020). These reductions in structural complexity likely affect habitat quality, as perennial tussock grasses represent fertile patches that support a more diverse soil microbial community, and greater levels of soil carbon and nitrogen (Northup *et al.* 1999). Reduced cover and size can also affect grassland-dependent fauna such as reptiles (Howland *et al.* 2016) and granivorous birds (Rees *et al.* 2017).

Little is known about the potential physical impacts of kangaroos on biocrusts, but given that the pressure exerted by kangaroos on the ground is lower than that of ungulates (Bennett 1999), we would expect them to have fewer physically disruptive effects on the soil than livestock (Eldridge 1998), and therefore relatively benign effects on a range of ecosystem functions. We found that kangaroo grazing was associated with a 70% sparser biocrust cover. Although statistically significant, a decline in biocrust cover from 4.1% to 2.4% is unlikely to be ecologically important. Nonetheless, kangaroos could influence biocrust composition by potentially increasing the abundance of grass-free patches that favour open area pioneering species (e.g. the nitrogen-fixing lichen *Collema coccophorum* Tuck.) at the expense of shade-tolerant mosses (Eldridge 1999). Similarly, greater litter cover under grazing could reduce suitable niches for shade-sensitive taxa (O'Bryan *et al.* 2009) such as *Fissidens* spp. mosses (Eldridge 1999). An increase in pioneering cyanobacteria and nitrogen-fixing lichens on bare patches could potentially lead to changes in soil nitrogen levels, with unknown effects on plant community composition.

Effects on biocrusts might also be indirect and mediated by declines in grass cover and therefore more area of unvegetated soil available for biocrust establishment. While we have very little information on the impacts of kangaroos on different biocrust taxa, our observations from the study area suggest strong increases in the cover of dryland mosses such as *Barbula calycina* Schwägr. and *Barbula crinita* Schultz and the lichen *Xanthoparmelia muelleri* (Hampe) Nyl. inside the exclosures. Studies conducted in exclosures where kangaroos have been excluded show a greater cover of biocrusts inside than outside (e.g. Read *et al.* 2011), but the extent to which kangaroos are the principal drivers is likely confounded by other herbivore effects outside the plots. The current study, however, is unique in that apart from kangaroos, there are no residual herbivores in the grazed plots other than very low numbers of rabbits and emus, though sheep grazing occurred in some areas, but was discontinued about 25 years ago. We can therefore

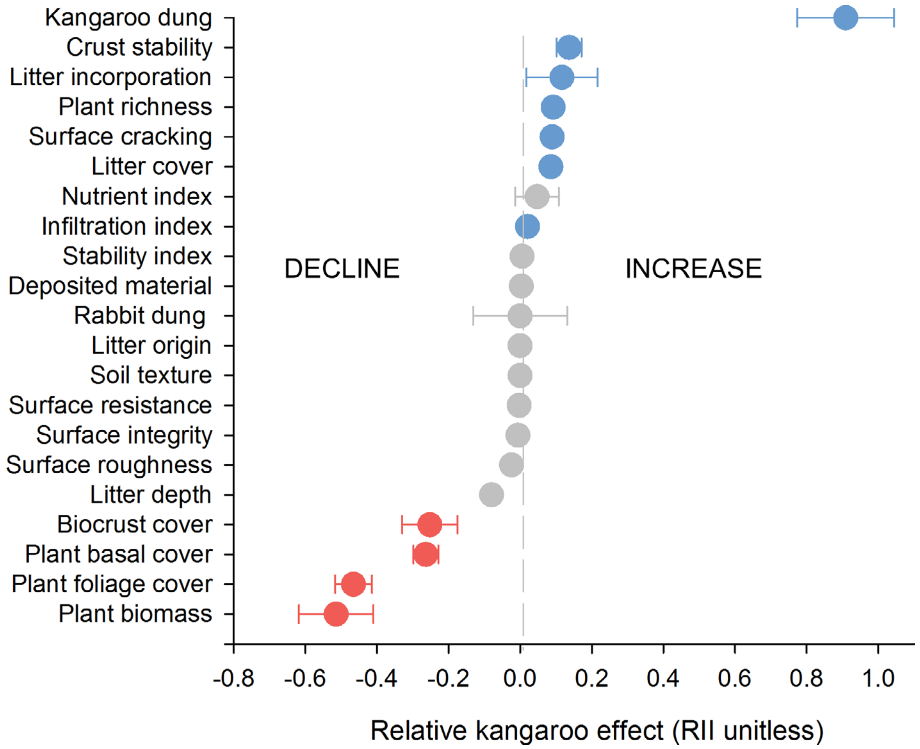

Figure 1. Relative (mean ± 95% CI) effect of kangaroos on the 21 response variables shown in Table 1. Increase/decline indicate the effect of kangaroo grazing with significant ($P < 0.05$) increase (blue) and decrease (red) shown by colour. The relative effect (RII) is calculated as $(X_{Grazed} - X_{Ungrazed})/(X_{Grazed} + X_{Ungrazed})$.

attribute changes in biocrusts largely to kangaroos.

Kangaroo grazing was associated with greater litter cover, and a change in median level of incorporation from nil to slight, and therefore greater partial breakdown of litter in the surface soil layers. Greater litter under grazing is likely due to two processes: first, kangaroos are highly selective (Ellis *et al.* 1977) and detached fragments of uneaten grass will contribute to litter build-up; and second, declines in grass cover and biomass are associated with greater unvegetated gaps among the grasses at the grazed sites that would likely trap eucalypt leaves. Given the greater incorporation of litter under kangaroo grazing, we would expect greater levels of soil multifunctionality (i.e. the ability of soils to provide multiple ecosystem functions simultaneously), in the presence of low levels of kangaroo grazing. While we did not assess soil nutrients, indirect evidence for this comes from global studies (Eldridge *et al.* 2019) showing that two of our surface measures, litter incorporation and soil surface integrity, were two strong predictors of soil multifunctionality in drylands, after accounting for the influence of climate and soil. Our study, however, does not consider appropriate stocking rates of kangaroos in this peri-urban environment. The soil profile is likely suffering from the legacy effects of a history of grazing, clearing and cropping since settlement. High densities of kangaroos in the early 2000s resulted in substantial loss of ground cover over large areas, with supplementary feeding needed to sustain the population. Thus, current soil conditions are almost certainly still recovering from the impacts of previous, higher densities of kangaroos. In temperate grasslands in the Australian Capital Territory (ACT 2010), kangaroo densities in the range of 60 to 150 animals/km^2 are regarded as fitting kangaroo conservation densities that sustain appropriate herbage biomass (ACT 2010). Given that the densities in our study were up to half those in the ACT Kangaroo Management Plan (ACT 2010), it is not unreasonable that effects of kangaroos on soil functional measures were largely benign.

Kangaroos are known to associate with high-quality habitat (Frank *et al.* 2016; Mutze *et al.* 2016) where plant richness is likely greater (Eldridge *et al.* 2018). In our study, we found that kangaroo grazing was associated with a 20% increase in plant species richness, consistent with other studies that have used kangaroo exclosures (e.g. Hunter & Hunter, 2019). A likely explanation is that grazing releases smaller plant species from competitive exclusion by larger species, generally grasses, by reducing the size and density of perennial grasses. These grasses were dominated by tussock forming Three-awned Speargrass and Shot Grass, both of which are known to compete strongly with other smaller ground-storey species. However, this does not necessarily mean that kangaroos are not having an effect on some species groups. Large areas of Wianamatta Regional Park have failed to exhibit their full floristic diversity due to the legacy effect of past disturbances, changes in fire history and intense grazing. We should not discount the possibility that kangaroos might impede the recruitment of some palatable species such as orchids and lilies.

The coastal dry woodlands in our study have probably always been grazed by kangaroos at various levels. At current densities, however, our study provides strong evidence that kangaroo grazing has not had any significant deleterious effects on those attributes of ecosystem health that are assessed by measuring surface soil features. Grazing was associated with greater crust stability, more litter incorporation and litter cover, greater plant richness, but reductions in productivity (grass biomass, grass cover). Greater crust stability could have resulted from changes in biocrust composition caused by kangaroo grazing, or indirect effects of kangaroo activity on microbial communities, both of which could increase soil aggregation and therefore surface stability. This increase in stability under kangaroo grazing is likely limited to situations where animal densities are low. Higher densities of kangaroos would likely have the opposite effects, though evidence for this is currently lacking. We acknowledge, however, that the effects of current and former levels of grazing on other measures of function, such as reptiles, birds and invertebrates, are largely unknown. What we can say, however, is that soil function, as assessed by changes in the morphology of the soil surface, is exhibiting a mixture of effects, with some increases and some declines, and no clear evidence of surface degradation. Finally, the greatest effect of kangaroos in this peri-urban reserve was a reduction in both plant cover and biomass. Given the importance of cover and biomass for habitat and soil protection, it seems reasonable that these would be the most useful attributes to use as potential management triggers on which to make decisions about reducing kangaroo densities.

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References

ACT (2010) *ACT Kangaroo Management Plan*. Parks, Conservation and Lands, Canberra, ACT.

Anderson M. J. (2014) *Permutational multivariate analysis of variance (PERMANOVA). Wiley statsref: statistics reference online*, 1–15. https://doi.org/10.1002/9781118445112.stat07841

Bailey K. and Alchin B. (2000) Comparative impact of livestock & kangaroos on rangelands. In: *11th Biennial Conference of the Australian Rangelands Society* (ed. J. N. S. Nicolson), pp. 198–199. Australian Rangeland Society, Broken Hill.

Bennett M. (1999) Foot areas, ground reaction forces and pressures beneath the feet of kangaroos, wallabies and rat-kangaroos (Marsupialia: Macropodoidea). *Journal of Zoology* **247**, 365–369.

Brunton E. A., Srivastava S. K., Schoeman D. S. and Burnett S. (2018) Quantifying trends and predictors of decline in eastern grey kangaroo (*Macropus giganteus*) populations in a rapidly urbanising landscape. *Pacific Conservation Biology* **24**, 63–73.

Caughley G., Shepherd N. and Short J. (1987) *Kangaroos: their Ecology and Management in the Sheep Rangelands of Australia*. Cambridge University Press, Cambridge, England.

Dawson T. J. (1995) *Kangaroos: biology of the largest marsupials*. Cornell University Press, Ithaca, New York.

De Cáceres M. and Legendre P. (2009) Associations between species and groups of sites: indices and statistical inference. *Ecology* **90**, 3566–3574.

Driscoll D. A. (2017) Disturbance maintains native and exotic plant species richness in invaded grassy woodlands. *Journal of Vegetation Science* **28**, 573–584.

Dufrêne M. and Legendre P. (1997) Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs* **67**, 345–366.

Eldridge D. (1998) Trampling of microphytic crusts on calcareous soils, and its impact on erosion under rain-impacted flow. *Catena* **33**, 221–239.

Eldridge D. J. (1999) Distribution and floristics of moss- and lichen-dominated soil crusts in a patterned *Callitris glaucophylla* woodland in eastern Australia. *Acta Oecologica* **20**, 159–170.

Eldridge D. J., Delgado-Baquerizo M., Quero J. L. *et al*. (2019) Surface indicators are correlated with soil multifunctionality in global drylands. *Journal of Applied Ecology* **57**, 424–435.

Eldridge D. J., Delgado-Baquerizo M., Travers S. K. *et al*. (2018) Livestock activity increases exotic plant richness, but wildlife increases native richness, with stronger effects under low productivity. *Journal of Applied Ecology* **55**, 766–776.

Eldridge D. J., Delgado-Baquerizo M., Travers S. K., Val J. and Oliver I. (2017) Do grazing intensity and herbivore type affect soil health? Insights from a semi-arid productivity gradient. *Journal of Applied Ecology* **54**, 976–985.

Ellis B., Russell E., Dawson T. and Harrop C. (1977) Seasonal changes in diet preferences of free-ranging red kangaroos, euros and sheep in western New South Wales. *Wildlife Research* **4**, 127–144.

Faast R. and Facelli J. M. (2009) Grazing orchids: impact of florivory on two species of Caladenia (Orchidaceae). *Australian Journal of Botany* **57**, 361–372.

Frank A. S., Wardle G. M., Greenville A. C. and Dickman C. R. (2016) Cattle removal in arid Australia benefits kangaroos in high quality habitat but does not affect camels. *The Rangeland Journal* **38**, 73–84.

Gowans S., Gibson M., Westbrooke M. and Pegler P. (2010) Changes in vegetation condition following kangaroo population management in Wyperfeld National Park. In: *Macropods: the biology of kangaroos, wallabies and rat-kangaroos* (eds. G. Coulson, and M. Eldridge), pp. 361–370. CSIRO Publishing, Collingwood, Vic., Australia.

Grice A. and Barchia I. (1992) Does grazing reduce survival of indigenous perennial grasses of the semi-arid woodlands of western New South Wales? *Australian Journal of Ecology* **17**, 195–205.

Henderson T., Rajaratnam R. and Vernes K. (2018) Population density of eastern grey kangaroos (*Macropus giganteus*) in a periurban matrix at Coffs Harbour, New South Wales. *Australian Mammalogy* **40**, 312–314.

Howland B. W., Stojanovic D., Gordon I. J. *et al*. (2016) 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., Stojanovic D., Gordon I. J., Manning A. D., Fletcher D. and Lindenmayer D. B. (2014) Eaten out of house and home: impacts of grazing on ground-dwelling reptiles in Australian grasslands and grassy woodlands. *PLoS One* **9**, e105966.

Hunter J. T. and Hunter V. H. (2019) High macropod populations at Look At Me Now Headland, North Coast NSW: implications for endangered *Themeda triandra* grasslands on coastal headlands. *Cunninghamia* **18**, 97–106.

Iles J., Kelleway J., Kobayashi T. *et al*. (2010) Grazing kangaroos act as local recyclers of energy on semiarid floodplains. *Australian Journal of Zoology* **58**, 145–149.

Koch J. M., Richardson J. and Lamont B. B. (2004) Grazing by kangaroos limits the establishment of the grass trees *Xanthorrhoea gracilis* and *X. preissii* in restored bauxite mines in eucalypt forest of southwestern Australia. *Restoration Ecology* **12**, 297–305.

Letnic M., Ritchie E. G. and Dickman C. R. (2012) Top predators as biodiversity regulators: the dingo Canis lupus dingo as a case study. *Biological Reviews* **87**, 390–413.

Maestre F. T. and Puche M. D. (2009) Indices based on surface indicators predict soil functioning in Mediterranean semi-arid steppes. *Applied Soil Ecology* **41**, 342–350.

McAlpine C., Grigg G., Mott J. and Sharma P. (1999) Influence of landscape structure on kangaroo abundance in a disturbed semi-arid woodland of Queensland. *The Rangeland Journal* **21**, 104–134.

McIntyre S., Cunningham R., Donnelly C. and Manning A. (2015) Restoration of eucalypt grassy woodland: effects of experimental interventions on ground-layer vegetation. *Australian Journal of Botany* **62**, 570–579.

Morris T. and Letnic M. (2017) Removal of an apex predator initiates a trophic cascade that extends from herbivores to vegetation and the soil nutrient pool. *Proceedings of the Royal Society B: Biological Sciences* **284**, 20170111.

Mutze G., Cooke B. and Jennings S. (2016) Density-dependent grazing impacts of introduced European rabbits and sympatric kangaroos on Australian native pastures. *Biological Invasions* **18**, 2365–2376.

Northup B., Brown J. and Holt J. (1999) Grazing impacts on the spatial distribution of soil microbial biomass around tussock grasses in a tropical grassland. *Applied Soil Ecology* **13**, 259–270.

NSW Scientific Committee (2009). *Coolibah-Black Box Woodland of the Northern Riverine Plains in the Darling Riverine Plains and Brigalow Belt South Bioregions-Reject Delisting of Ecological Community*. NSW Scientific Committee, Sydney. [accessed 6 January 2012.] Available from URL: www.environment.nsw.gov.au/determinations/coolibahblackboxrejectdelistfd.htm.

O'Bryan K., Prober S., Lunt I. and Eldridge D. J. (2009) Frequent fire promotes diversity and cover of biological soil crusts in a derived temperate grassland. *Oecologia* **159**, 827–838.

Price J. N., Wong N. K. and Morgan J. W. (2010) Recovery of understorey vegetation after release from a long history of sheep grazing in a herb-rich woodland. *Austral Ecology* **35**, 505–514.

Rafferty C., Lamont B. B. and Hanley M. E. (2005) Selective feeding by kangaroos (*Macropus fuliginosus*) on seedlings of *Hakea* species: effects of chemical and physical defences. *Plant Ecology* **177**, 201–208.

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.

Read C. F., Duncan D. H., Vesk P. A. and Elith J. (2011) Surprisingly fast recovery of biological soil crusts following livestock removal in southern Australia. *Journal of Vegetation Science* **22**, 905–916.

Rees J. D., Kingsford R. T. and Letnic M. (2017) In the absence of an apex predator, irruptive herbivores suppress grass seed production: implications for small granivores. *Biological Conservation* **213**, 13–18.

Robertson D. (2017) *Analysis of the response of cumberland plain woodland to grazing by macrofauna on the SMP*. Cumberland Ecology, Sydney NSW, Australia.

Tongway D. (1995) Monitoring soil productive potential. *Environmental Monitoring and Assessment* **37**, 303–318.

Tozer M. (2003) The native vegetation of the Cumberland Plain, western Sydney: systematic classification and field identification of communities. *Cunninghamia* **8**, 1–75.

Tozer M., Turner K., Keith D. *et al*. (2010) Native vegetation of southeast NSW: a revised classification and map for the coast and eastern tablelands. *Cunninghamia* **11**, 359–406.