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Does reducing grazing pressure or predation conserve kowaris? A case study at Diamantina National Park

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ABSTRACT

Livestock contributes to the decline of many species in Australia. However, they may have less impact in arid environments, where annual plant species dominate. Kowaris (*Dasyuroides byrnei*), a small carnivorous marsupial, living on Diamantina National Park were monitored to assess the success of ecosystem recovery following a reduction in cattle. Kowaris were found at 10 locations within the study area: five where they had been recorded prior to the area becoming a national park and five 'new' locations. No kowaris were found at one of the historical sites. The density was estimated to range from 1 to 2.5 kowaris per square kilometre from 2007 to 2009. The results suggest that the population likely increased following a reduction in grazing pressure. However, a boom in rodents and predators occurred during the study with a corresponding decline in kowari detections. Kowaris have not been detected at any of the study sites since 2012. These results suggest that management of top-down factors as well as bottom-up factors are required to conserve kowaris. The work further highlights the need for replicated, long-term studies if the interactions between complex ecological processes, at a landscape scale, are to be understood so that threatened species, like the kowari, can be managed effectively.

Keywords: arid zone, cat, cattle grazing, *Dasyuroides byrnei*, dingo, monitoring, predation, *Rattus villosissimus*, threatened species, top-down and bottom-up effects.

Introduction

Understanding the role that bottom-up (food and habitat limited) and top-down (predation limited) drivers have on threatened mammal species populations is critical to their management. However, undertaking robust grazing and predator removal experiments can be problematic in unfenced arid landscapes and, as a result, the impacts of grazing and predation are not well understood, particularly for some small mammal communities (Read and Cunningham 2010). Arid systems are prone to boom-and-bust events where rainfall, or the lack of it, and introduced predator populations can confound data and alter the balance between drivers (Letnic and Dickman 2006). The stocking rates on neighbouring properties can also vary considerably across the landscape and over time, which can confound data and make ascribing changes to a particular management regime difficult.

Cattle grazing is known to contribute to the loss of species diversity and the destruction/simplification of habitats (Friedel *et al.* 1990; Morton 1990; Bastin *et al.* 1993; Abensperg-Traun *et al.* 1996; Read and Cunningham 2010; Fensham *et al.* 2019; Silcock *et al.* 2019; Neilly *et al.* 2021). The impact of grazing on vegetation is better studied in comparison to mammals, but the dynamics of the semi-arid and arid systems are complex, and some studies suggest that removing stock does not always result in improvements to the vegetation (Read 1999; Page 2001; Fensham *et al.* 2010; Silcock and Fensham 2013, 2019). In part, this is because distinguishing between the effects of rainfall and the effects of cattle grazing on species richness can be difficult. The impact of grazing in the arid zone of Australia may also be less severe because the habitats are dominated by annual and ephemeral plant species, which naturally senesce and break down each year (Fensham *et al.* 2010;

Silcock and Fensham 2013, 2019). The impact of cattle on fauna communities is considered to be principally through their effect on vegetation and how this affects the ability of native fauna to find shelter and food (Friedel 1990, 1997; Read and Cunningham 2010; Frank *et al.* 2013; Neilly *et al.* 2016; Neilly and Schwarzkopf 2018).

Kowaris are a small (up to 175 g), carnivorous marsupial that live on the ironstone plains in western Queensland, and South Australia (Lim 2008). They are usually solitary, and males and females have a mean home range size of between 9.0 and 10.3 km^2, respectively (Lim 2008). Kowaris are listed as 'Vulnerable' under the *Queensland Nature Conservation Act 1992* and the *Environment Protection and Biodiversity Conservation Act 1999*, 'Endangered' under the South Australian *Endangered Species Protection Act 1992* and 'Extinct' under the Northern Territory's *Territory Parks and Wildlife Conservation Act 2000*.

Kowari populations are known to increase episodically across their range in response to rainfall and prey populations – in particular, insects (grasshoppers) (Greenville *et al.* 2018) and juvenile long-haired rats (*Rattus villosissimus*) (Lim 1992), which can plague following above average rainfall (Greenville *et al.* 2013). In addition to grazing impacts, predation is considered a threat to kowaris (Palmer 1999). Predators include owls, dingoes (treated here as including dingoes (*Canis familiaris*), feral dogs (*C. familiaris*) and their hybrids), feral cats (*Felis catus*), and large reptiles (snakes and goannas) (Lim 1992, 1998; Palmer 1999; Greenville *et al.* 2018; Woolley *et al.* 2019). However, the nature of how these top-down (predation) and bottom-up (prey) drivers interact and affect kowaris, and small mammal populations in general, is largely unknown. Lim (1992), Maxwell *et al.* (1996) and Brandle *et al.* (2002) have suggested that there is likely to be a link between cattle grazing intensity and kowari population density, mainly because of the effect cattle have on altering vegetation communities. Cattle have been implicated in the disappearance of kowaris from Sandringham Station (Maxwell *et al.* 1996).

In 2006, a project was initiated on Diamantina National Park (hereafter Diamantina or the Park) to investigate ecosystem recovery as well as the conservation of the threatened kowari following efforts to substantially reduce stray stock on the Park. At Diamantina, cattle grazed the vegetated drainage lines (in addition to the landscape more broadly) and disturbed mammal burrows (McRae 2004; Woinarski *et al.* 2014). The vegetated drainage lines provided important refuges for invertebrates and small vertebrates, which in turn provided food for kowaris (Lim 1992). The aim of this study was to use long-term monitoring data to determine if the size and distribution of the kowari population on Diamantina changed following a reduction in grazing pressure and in the process, compare the relative influence of other drivers, including predation. We present 15 years of survey data, compare them to historical records collected from Diamantina and to more recent records obtained from the nearby Astrebla Downs National Park (Astrebla) and compare vegetation structure and composition data between on- and off-park sites.

Materials and methods

Study area

Diamantina is located 306 km south-west of Winton in central Queensland. The 507 000 ha area was made a national park in 1992 to conserve 'the high number of landscape types, land zones, land systems and associated vegetation types typical of the northern Channel Country and Mitchell Grass Downs Bioregions – a mix not achieved elsewhere' (Wilson and Mitchell 1992; Sattler 2014). Prior to becoming Diamantina in the 1990s, the property was managed as a cattle station and at times had over 12 000 head of cattle (Barry 2007). The Park has largely been destocked but large cattle grazing enterprises surround Diamantina, with the exception being Pullen Pullen – a Special Wildlife Reserve to the north, and stray stock continue to graze (up to approximately 1000 head: C. Mitchell, QPWS, pers. comm., 2020) the Park, albeit at a much-reduced scale. Ranger staff constructed and repaired boundary fences, restricted access to water points and organised cattle musters. The Park includes several 'of concern' regional ecosystems and provides habitat for many threatened flora and fauna species, and internationally listed species including the iconic greater bilby (*Macrotis lagotis*), kowari, night parrot (*Pezoporus occidentalis*), plains wanderer (*Pedionomus torquatus*), plains mouse (*Pseudomys australis*) and dusky hopping-mouse (*Notomys fuscus*). This study was conducted in the south-east section of Diamantina – an area that was approximately 54 000 ha in size. The study area was dominated by large sections of ironstone downs – an open rocky landscape that often provides habitat for kowaris. Adjacent to the ironstone downs are often large ashy clay plains, sand dunes, low hills and claypans. Several creeks flow through the area and the Diamantina River runs north to south along the western edge of the study area, which includes a large blue bush swamp.

The mean annual rainfall at Diamantina is approximately 260 mm (Australian Government Bureau of Meteorolgy (BOM) 2021). Most of this rain falls between December and March but there is considerable year-to-year variation in timing. The survey work was conducted when temperatures were mild (15–32°C). Daily summer temperatures often exceed 35°C and winters can be cool with a mean minimum temperature of 7°C.

Vegetation

Vegetation was measured within or adjacent to the kowari trapping sites, including six ironstone downs sites on-park (low grazing), and two ironstone downs sites on the neighbouring property – Davenport Downs (highly grazed). Fifty metre transects, running north–south, were used to record the vegetation twice a year in 2007, 2008, 2009, 2011 and 2012 and annually in 2010 and 2013. The foliage projective cover (FPC) of the understorey; understorey species composition, frequency and dominance; soil disturbance and biomass were recorded at each site. A detailed description of the methodology along with the site location details are provided in Appendix 1. We used a paired *t*-test to look for differences in the on- and off-park ironstone downs vegetation sites. We also undertook a basic regression analysis in Excel comparing six monthly rainfall totals, recorded at the Diamantina River Gauging Station (data supplied by the Department of Regional Development, Manufacturing and Water) with the average amount of cattle-related soil disturbance, and the percentage cover of forbs, and perennial and annual grasses.

Kowari predator/prey assessment

Repeated, vehicle-based, line transect surveys using two 100 W spotlights were conducted, both on- and off-road, to search for kowaris and their predators and prey twice a year in 2007, 2008, 2009 and 2011 and annually in 2010, 2013 and 2017. After it was found that thermal cameras (FLIR MD625) could be used to improve the detection of small mammals by up to five times compared with spotlights (Augusteyn *et al.* 2020*a*), they were used instead of spotlights. They were used annually from 2014 to 2021, except in 2016 and 2019 when there was nil survey effort. The vehicle was driven at 10–15 km/h with two observers standing in the tray, one on each side of the vehicle. In 2020 and 2021, three thermal cameras (Two Flir MD625 and a Tau2) were used, each with their own observer. All surveys were conducted between 2000 hours and 0100 hours. All fauna observed along the transects, including prey and predators of kowaris, were recorded. The details of these surveys have been divided into two groups – those conducted in suitable kowari habitat (ironstone dominated) and those conducted adjacent to the suitable habitat (ashy clay soils and drainage lines adjacent to the ironstone dominated plains). Between 23 and 54 km of transect were surveyed within suitable ironstone habitat and between 32 and 98 km were surveyed that included both suitable kowari habitat and habitat adjacent to the suitable kowari habitat. The habitat adjacent to the kowari habitat was included to survey for predators. The length of the transects conducted within the kowari habitat is provided in Appendix 2. The details for the transects adjacent to the kowari habitat are provided in Appendix 3. Survey transects conducted through the trapping grids (Appendix 4) were completed either before or after the trapping commenced at a site so that the spotlighting did not affect the trapping. In addition to the spotlight/TIC surveys, all kowaris observed incidentally while staff were carrying out other activities were recorded.

Kowari distribution

Historical records

The Department's wildlife record system – WildNet (WN) and the Atlas of Living Australia (ALA) (Atlas of Living Australia website at http://www.ala.org.au, accessed 28 June 2005) were searched for records of kowaris to help identify suitable kowari habitat on Diamantina. Researchers who had previously conducted small mammal surveys/monitoring on the Park were also contacted to determine whether there were locations not captured in the aforementioned databases.

Trapping and nocturnal searches

Elliott traps were initially used to locate kowaris in April and September 2007 (Fig. 1). These presence/absence surveys were conducted in areas where kowaris had been trapped previously or where the habitat looked similar to that of known kowari capture sites. The location details of these presence/absence sites are provided in Appendix 5.

The Elliott traps were set for three nights and were placed 100 m apart and baited with either a bolus of peanut butter, rolled oats, sardines, sesame seed oil and cat biscuit or dog biscuit soaked in fish oil or mixed with sardines. The bait type used was changed daily, with the type being selected randomly, to reduce the chance of any caught kowaris developing a negative association with the bait. The traps were checked early in the morning and all animals caught were released at the site of capture if it was prior to sunrise. Animals found in traps after sunrise were kept in calico bags and stored indoors in a cool dark cupboard during the day and released at the place of capture after sunset. This was done to reduce the chance of a captured animal being preyed upon after they were released – before they had a chance to find and retreat to their burrow. The traps were closed during the day and reopened each afternoon. A peg fashioned out of a piece of reinforced steel mesh was used to secure the trap in place and reduce the chance of it blowing away during strong wind events/dust storms (Fig. 2).

Camera survey

In April 2018, 85 Reconyx PC850 white flash remote cameras were deployed at four of the trapping sites (20–23 per site) where kowaris had been trapped previously (see below in Kowari Density) (Sites 2, 8, 9, and 11) to determine their presence/absence. The cameras were placed in a grid, approximately 200 m apart – generally at every second Elliot trap location used between 2007 and 2012. The cameras were attached to a 600 mm long wooden garden stake and left in place for 11 nights. Cameras were baited with a bolus of peanut butter, rolled oats and sardines placed in a canister pegged to the ground 1 m in front of the camera. The cameras were set to take still images 24 h per day, with five images per trigger and no quiet period between triggers.

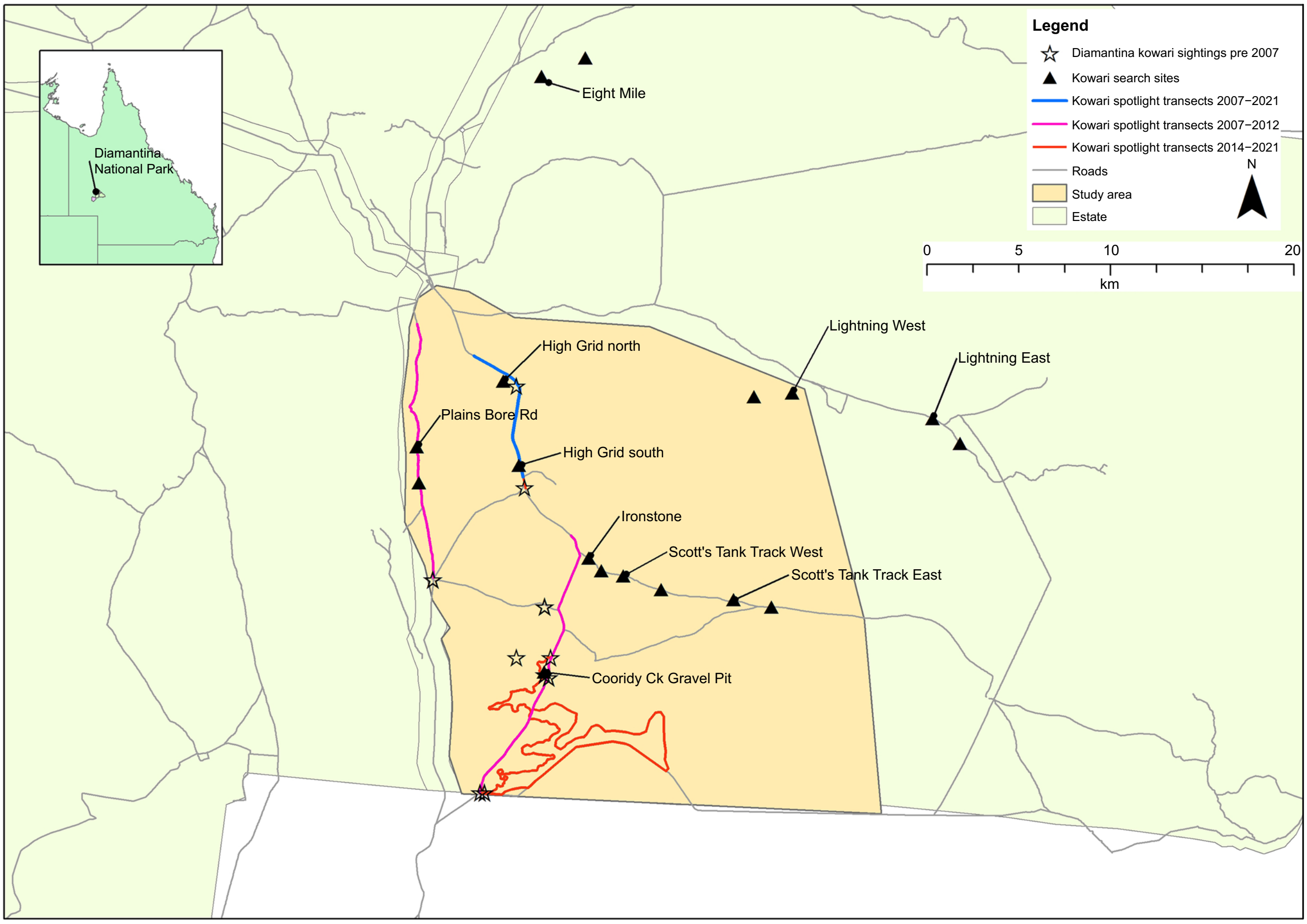

Fig. 1. A map of the kowari search sites (▲) from this study and the historical sites (☆) that were obtained from a search of the WN and ALA databases. Datum GDA94, UTM Zone 54.

Kowari density

To track changes in the size of the kowari population, up to six trapping grids (4 km^2) were monitored twice a year in 2007, 2008, 2009 and 2011 and annually in 2010 and 2012. The grids were placed in areas containing suitable ironstone habitat and in areas where the species had previously been recorded. These grids were separate from the trapping transects used to initially locate kowaris. The density of kowaris was initially assessed at four grids (4 km^2) (Sites 5, 8, 9, and 11) with 80 Elliott traps placed every 100 m along four 2 km long parallel transects (20 traps per transect) spaced 660–680 m apart (Appendix 5). In April 2008, two more grids (Sites 2, 3, 4), were surveyed with the same arrangement and number of traps used previously. In April 2009 and in subsequent surveys, sampling effort was reduced and only 40 traps were used per site. Their placement along a linear transect was selected based on landscape features and kowari captures that occurred in 2007 and 2008. Prior to 2009, traps remained opened for three nights. In 2009 and thereafter, traps were opened for four nights. The traps were baited with the same bait types described earlier for Elliott trapping.

Each captured kowari was measured (hind foot length, head–body length, tail length), DNA sampled (hair follicle), weighed and microchipped (Trovan ID100 (1.25 mm × 7 mm) Nanotransponder). The Schnabel method (Schnabel 1938), for a closed population, was used to calculate density. Abundance was estimated by multiplying the density by the survey area (4 km^2). Abundance and density were not able to be calculated for most grids or years due to the low number of individuals caught and the low number of recaptures.

Results

Vegetation

The mean species richness for each plant group (forbs, perennial and annual grasses) varied across years but was generally low (<5) except for forbs in autumn 2010 and

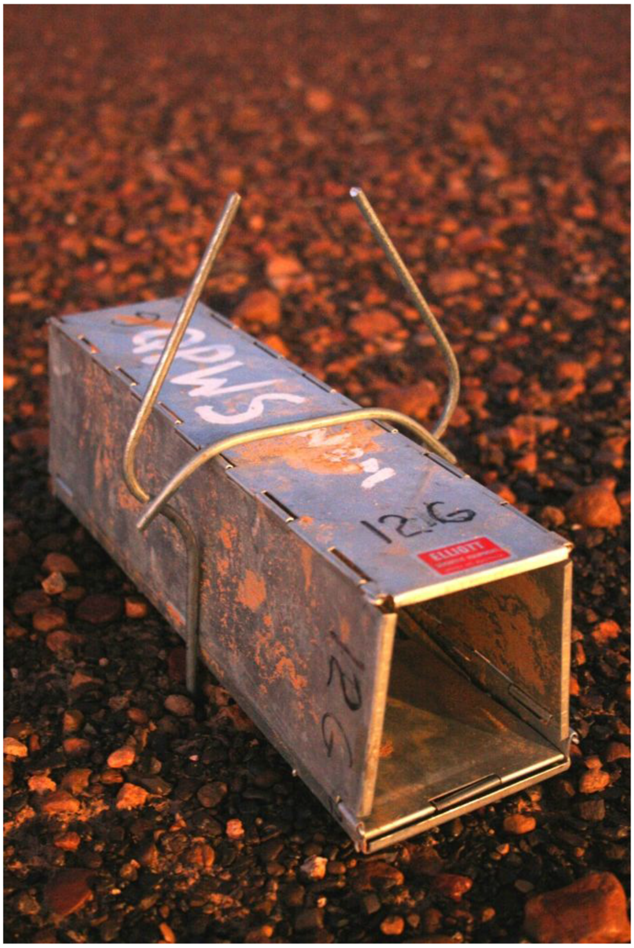

Fig. 2. An Elliott trap with a peg that was developed during the project that could push into the ground and hold the trap in place during wind events.

2011 and spring 2012, when species richness increased (>7) (Fig. 3). Species richness for all plant groups weakly correlated positively with six monthly rainfall totals, particularly summer–autumn rainfall (forbs $y = 23.297x + 85.63$ ($R^2 = 0.5259$), annual grass $y = 57.909x + 46.747$ ($R^2 = 0.7767$), and perennial grass $y = 87.414x + 75.577$ ($R^2 = 0.6855$)). Forbs were present at most of the vegetation sites throughout the year, both on- (low grazing) and off-park (higher grazing), with a large increase in the mean percentage cover at all sites occurring after 2011. Even though the percentage cover of forbs off-park was higher than on-park in most years, the difference was not significant. However, there was significantly more grass cover ($t_{10} = 1.812$, $P = 0.0001$) and more biomass ($t_{11} = 1.795$, $P = 0.03$) on-park than off-park and there was significantly less ($t_{11} = 1.795$, $P = 0.009$) soil disturbance by stock on-park than off-park. The number of grass species on-park was also significantly greater than off-park ($t_{10} = 1.812$, $P = 0.0001$).

Kowari predator/prey assessment

The number of kowari predators (e.g. feral cats and dingoes) observed on spotlight transects was relatively low until 2010, after which their numbers, in particular those of feral cats, spiked (Fig. 4). We recorded more kowari prey species after 2009, except kultarrs (*Antechinomys laniger*) whose populations appeared to be more abundant before 2009 (Fig. 5).

Kowari distribution (presence/absence)

Prior to this study, WN and the ALA contained a total of six historic kowari areas (an area was determined to be 9 km^2 – the kowari's mean home range: Lim 2008) from 10 sightings on Diamantina. Of these six historic areas, kowaris were detected at five during the current study – Sites 2, 6, 7, 9, and 11 (Fig. 6). Since 2007, kowaris have been recorded in 10 sites within the study area including five that are new areas – Sites 1, 3, 4, 5, and 10. Ten kowaris were caught in Elliott traps during the line transect trapping in 2007 as part of the initial search for kowaris and then a further 24 kowaris were seen across all spotlight surveys. In total, 78 kowaris (including recaptures) were caught in Elliott traps set as part of the density surveys during 2007–2012. The numbers of individual kowaris caught and observed are shown in Table 1. These numbers may include individuals that were both caught in a trap and spotlighted during a survey. After 2012, kowaris were not detected at any of the study sites.

All the sites supporting kowaris contained ironstone downs habitat or were near the edge where the ironstone and surrounding clayey plain met. Drainage lines intersected most sites that contained kowaris. These drainage lines often contained a mixture of grass and shrub species.

Kowari density

The density ranged from 1 to 2.75 kowaris per square kilometre. The density and abundance estimates and 95% CI for all sites where there were sufficient recaptures, are presented in Table 2. The number of individuals and the recaptures caught in the grids is provided in Appendix 6. The low number of recaptures meant that we were only able to produce meaningful estimates on six occasions (five grids and four seasons). Environmental factors, such as rain and windstorms which sometimes blew traps away (traps did not contain kowaris at the time), and corvids who opened traps and removed bait, made trapping difficult at times. Long-haired rats were detectable during 2008–2012 but only occurred in large numbers in two trips in 2011, when they interfered with traps and reduced our ability to sample the kowari population. During the plague of long-haired rats in 2011, the Elliott traps often contained multiple rats, with one trap containing four long-haired rats.

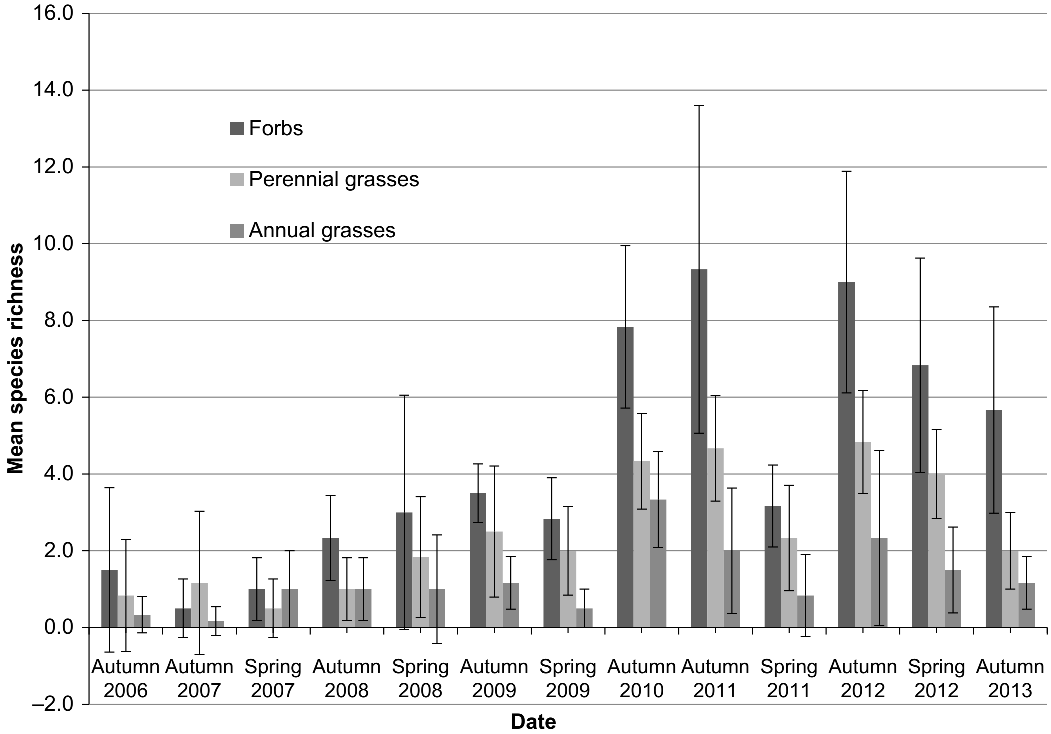

Fig. 3. Mean species richness of each plant group for all ironstone sites on-park. The standard deviation is shown.

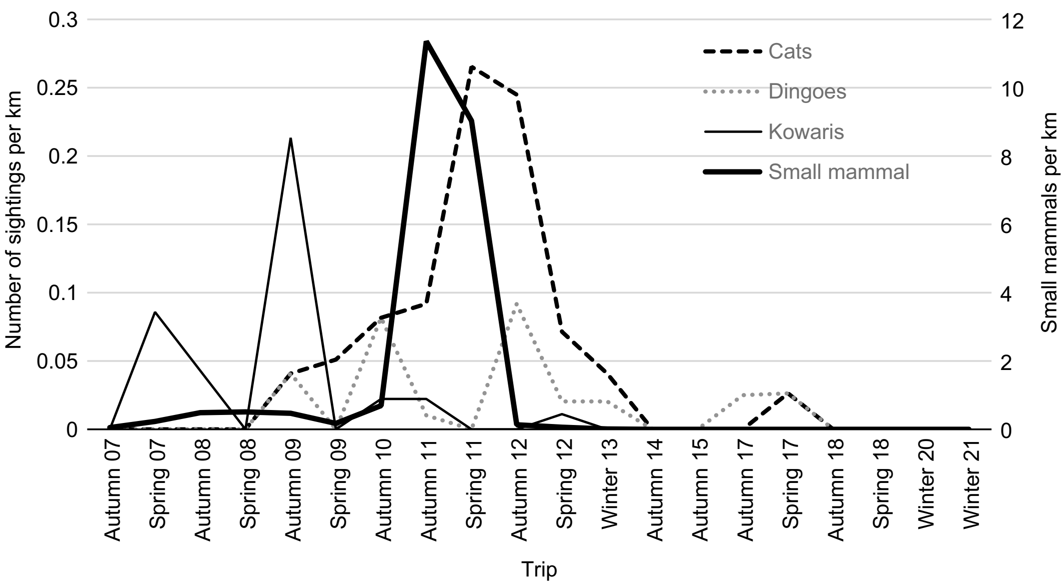

Fig. 4. The number of kowaris, small mammals and kowari predators (cats and dingoes) observed on the standard spotlight transects, 2007–2021. The number of small mammals is plotted on the secondary *y*-axis so that it did not distort the graph due to the higher numbers detected.

At Diamantina, kowaris appear to have a reasonably large home range. Several animals that were caught and released were recaught several hundreds of metres from where they were released. One individual travelled more than 2 km between Elliott traps in a single night.

Discussion

Reducing livestock grazing initially appeared to benefit the vegetation, kowaris and small mammals on Diamantina. However, any possible benefit of reduced grazing on

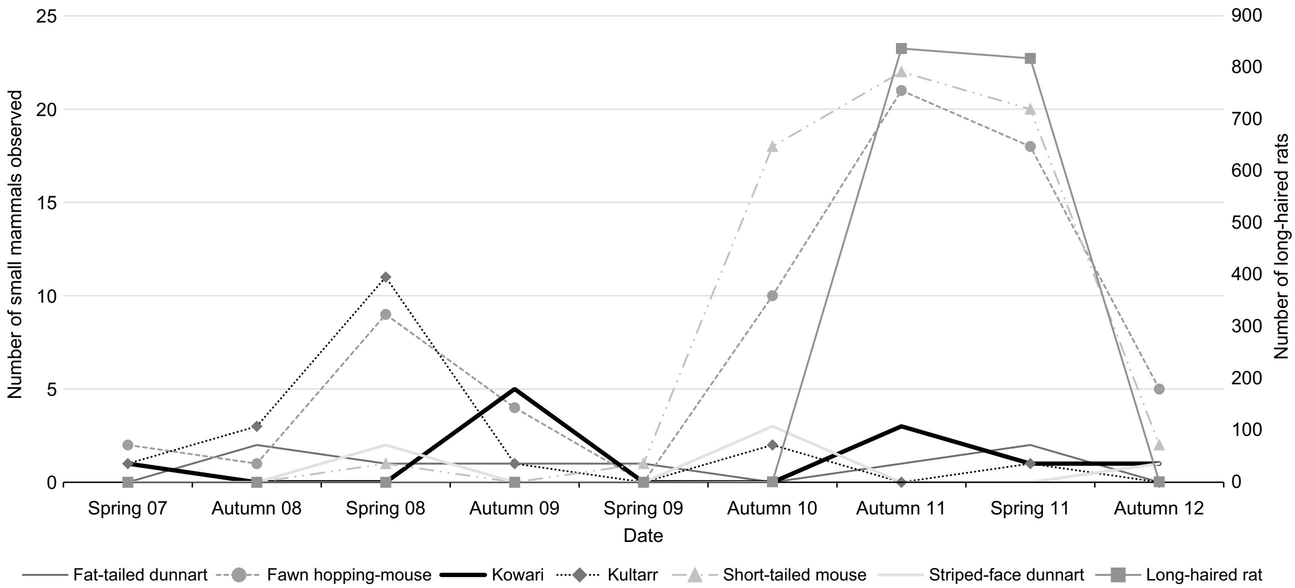

Fig. 5. Small mammals observed on the standard spotlight transects, 2007–2012. The number of long-haired rats is plotted on the secondary *y*-axis so that it did not distort the graph due to the high numbers detected.

kowari prey and the kowari population appears to have been over-ridden by an increase in predators. No kowaris were detected between 2013 and 2021 within the study area, suggesting that the kowari population didn't recover following a boom of resources and predators in 2011/12. The study highlights that controlling grazing alone is not enough to conserve threatened mammal species like the kowari and it is important to control predators as well. This finding is similar to that of Neilly *et al.* (2021), who found that destocking pastoral properties is rarely sufficient on its own to lead to ecosystem recovery and land managers must deal with a complex legacy of impacts when converting pastoral land to conservation reserve. Similarly, Read and Cunningham (2010) found that reducing stocking rates alone was insufficient to facilitate the restoration of an arid zone mammal community and predator control was critical to conserve mammals.

The role of vegetation, kowari predators and prey in determining kowari population size

There were significant differences in the amount of cattle related soil disturbance, and the percentage cover of grass, between sites on- and off-park – the former being greater off-park and the latter greater on-park. According to Mitchell (2022), the species composition on Diamantina has slowly changed after gazettal from a landscape dominated by *Sclerolaena* species to one with more grass and forbs other than *Sclerolaena* species. Most of this change occurred prior to the commencement of our study in 2007. The percentage cover of forbs, including *Sclerolaena* species, was higher off-park (heavily grazed) than on-park (lightly grazed) for most years. This may be because cattle preferentially graze on grass and soil disturbance is known to stimulate the growth of some forbs, including *Sclerolaena* species. Frank *et al.* (2013) found that neither vegetation nor small vertebrates responded immediately to the removal of livestock, but that rainfall events and cumulative grazing history were the key determinants of flora and fauna health in arid grasslands. They found the reproductive output of vegetation was greater in areas ungrazed for two years or more compared to areas still being grazed. Page (2001) found that a reduction of grazing pressure improved vegetation composition in the Mulga Land systems but, like Frank *et al.* (2013), found that rainfall had by far the greatest impact on plant biomass. These examples and the results from this study highlight the difficulties of monitoring ecosystem change in arid landscapes where large changes in biomass can occur regardless of other drivers, particularly in the absence of paired controlled sites.

Above average rain in 2009/10 resulted in a plague of long-haired rats in 2011 and an associated boom in predators (raptors and owls, monitor lizards, snakes, feral cats and dingoes), a phenomenon that also occurred at nearby Astrebla (Rich *et al.* 2014). This was the first major boom event to occur in the area since Diamantina became a national park. Despite the apparent increase in resources available to kowaris, their numbers unexpectedly declined. This contrasted with Lim (1998), who recorded an increase in kowaris, during and immediately after a rat plague and a decline during a plague of locusts. He suggested that the lack of rainfall at the time, and its effect on habitat quality had a greater effect on kowaris than the number of locusts. However, this does not accord with the results of Greenville *et al.* (2018) at Clifton Hills pastoral lease, who found

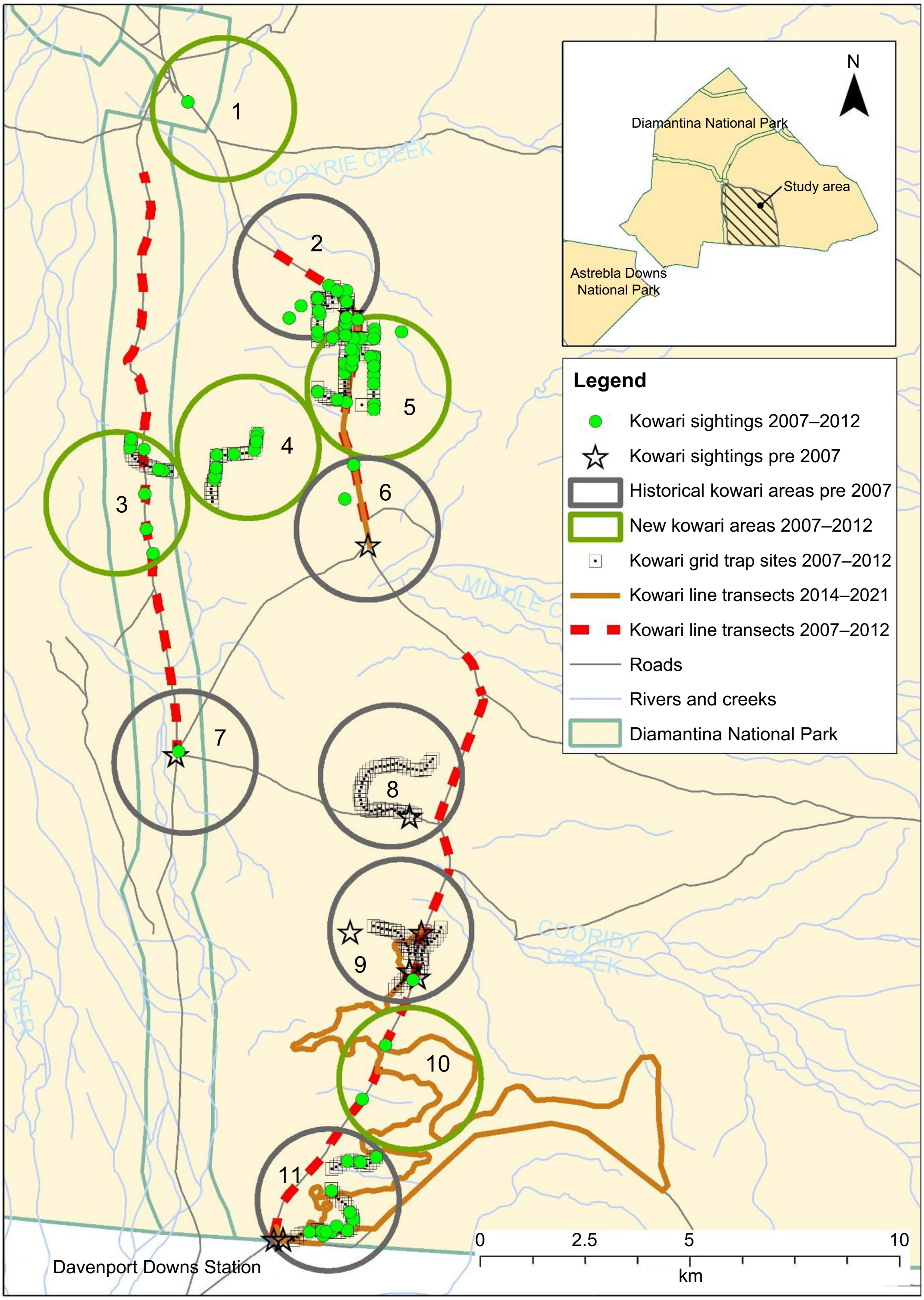

Fig. 6. Map of the study area showing the location of all kowaris trapped or seen between 2007 and 2012 in the south-east section of Diamantina. The line transects and trapping grids used during this study and the historical kowari records (before gazettal) are also shown. (Datum GDA94, UTM Zone 54.) The circles are a subjective representation of the mean home range for kowaris (9 km^2). It is possible that the actual home ranges of the kowaris overlap those of other nearby kowaris and it is assumed that the historical trapping areas where the kowaris were previously found are similar to the trapping areas used in the current study.

Table 1. The number of individual kowaris caught and observed per survey, method and survey effort, 2007–2021.

Trip date	Survey method					Kowaris per kilometre	Kowari per trap night
	ELT	INC	SPF	TIC	Cam		
Autumn 07	10	1	N/A	N/A	N/A	N/A	0.006
Spring 07	4	0	2	N/A	N/A	0.09	0.003
Autumn 08	14	1	1	N/A	N/A	0.04	0.029
Spring 08	4	0	0	N/A	N/A	0	0.008
Autumn 09	9	0	8	N/A	N/A	0.21	0.009
Spring 09	10	1	0	N/A	N/A	0	0.010
Autumn 10	3	1	2	N/A	N/A	0.05	0.003
Autumn 11	3	3	6	N/A	N/A	0.16	0.003
Spring 11	4	0	3	N/A	N/A	0.08	0.004
Autumn 12	6	0	1	N/A	N/A	0.03	0.006
Spring 12	N/A	0	1	N/A	N/A	0.03	N/A
Winter 13	N/A	0	0	N/A	N/A	0	N/A
Autumn 14	N/A	0	N/A	0	N/A	0	N/A
Autumn 15	N/A	0	N/A	0	N/A	0	N/A
Autumn 17	N/A	0	0	N/A	N/A	0	N/A
Spring 17	N/A	0	N/A	0	N/A	0	N/A
Autumn 18	N/A	0	N/A	0	0	0	0
Spring 18	N/A	0	N/A	N/A	N/A	N/A	N/A
Winter 20	N/A	0	N/A	0	N/A	0	N/A
Winter 21	N/A	0	N/A	0	N/A	0	N/A

This table does not include animals that were recaught during a survey, just individuals, but it may include animals that were caught in traps and spotlighted in the same survey. Kowaris per kilometre is the number of kowaris seen on the spotlighting transects (spotlights or TIC) divided by the transect length and kowaris per trap night is the number of kowaris caught in an Elliott trap or camera divided by the number of trap nights.
ELT, Elliott trap; INC, incidental observation that includes animals detected using a spotlight outside of a spotlight transect and kowari signs such as footprints or scats; SPF, animals detected on a standard spotlight transect; TIC, thermal image cameras; CAM, remote camera surveys.

Table 2. Abundance and density estimates with 95% CI for trap sites and seasons where there were sufficient captures to enable an estimate to be calculated using the Schnabel method.

Date	Site	Abundance	Density per km^2
Autumn 2007	High Grid	8 (7.75–8.24 95% CI)	2 (1.93–2.06 95% CI)
Autumn 2008	High Grid	11 (10.7–11.2 95% CI)	2.75 (2.67–2.82 95% CI)
	Plains Bore	4 (3.20–4.79 95% CI)	1 (0.80–1.19 95% CI)
	Senna Gully	8 (7.77–8.22 95% CI)	2 (1.94–2.05 95% CI)
Autumn 2009	Bilby South	5 (4.36–5.63 95% CI)	1.25 (1.09–1.40 95% CI)
Spring 2009	Plains Bore	4 (3.20–4.79 95% CI)	1 (0.80–1.19 95% CI)

kowari numbers to be higher when locusts were abundant and lower after the rat plague. Greenville *et al.* (2018) found that kowaris declined on Clifton Hills regardless of climatic conditions and suggested they were under stress from extrinsic factors such as predation. This was similar to what was observed on Astrebla where the kowari population did recover (refer to Appendix 7), despite experiencing a rainfall pattern similar to that at Diamantina and being destocked (Orr 1986). Not only was the predator control effort on the two parks vastly different but Astrebla is further away from the Diamantina River, an area that is thought to provide refuge to predators during drought (Palmer 1999). Over 3000 feral cats and at least 66 dingoes/wild dogs were shot/baited at Astrebla between 2012 and 2021 (Rich *et al.* 2014; Augusteyn *et al.* 2020*b*) whereas fewer than 100 cats were shot or trapped and no dingoes were removed from Diamantina between 2006 and 2021 (unpublished QPWS data). Predator control by spotlight shooting on Diamantina is more difficult than at Astrebla because of the greater number of thickly vegetated drainage lines. The permanent presence of rabbits at Diamantina compared to Astrebla might be another factor that hampered recovery at Diamantina. Rabbits are known to support larger populations of predators than is otherwise possible (Cruz *et al.* 2013; Pedler *et al.* 2016) and this is particularly problematic during drought when rabbit numbers decline, and the predators are forced to seek alternative prey (Lim 1998).

Stobo-Wilson *et al.* (2020) highlighted that, in northern Australia, complex productive habitats enhanced the capacity of native mammals to cope with cat and dog predation whereas reduced habitat complexity and productivity increased top-down pressures and caused declines across much of the native mammal assemblage. The results of our study indicate that the enhanced productivity and improved habitat complexity observed on Diamantina, following a reduction in grazing, did not override the top-down pressures of predation following a spike in predator numbers. Like the small mammals, the predator populations also likely benefitted from the increased resources following a reduction in grazing which has then put pressure on the small mammal community. The ephemeral nature of the vegetation at Diamantina may mean that the benefits of reduced grazing are only temporary and that a spike in predators when the vegetation is senescing or has been consumed by rodents, i.e. at the end of the boom/start of the bust, is sufficient to remove most of the protective cover and favour the predators. For some species, like the yellow-footed rock-wallaby (*Petrogale xanthopus*), populations tend to follow the ebb and flow of resources (Sharp and McCallum 2010). However, at Diamantina the kowari population did not return to their pre-boom population size once conditions improved but decreased to levels that were well below it. This suggests that predation pressures play a greater role than habitat condition and prey availability in determining the survival of kowaris living at Diamantina.

The role of dingoes/wild dogs

Wijas and Letnic (2021) suggested that for some prey species the top-down effects of the dingo can have primacy over bottom-up effects on population dynamics. Other ecologists have suggested that dingoes may protect smaller prey from feral cats and foxes (*Vulpes vulpes*) (the latter are rarely seen in the area) (McRae 2004; Murphy *et al.* 2018), in habitats that have little cover, through mesopredator release (Moseby *et al.* 2019). Consistent with the mesopredator release theory, Wallach and O'Neill (2009) predicted that the retention of an uncontrolled dingo population in the landscape would facilitate the conservation of small mammals like the kowari. However, at Diamantina at the end of the boom when resources were running out, feral cats were observed in open habitats well away from the protective creek lines despite the presence of dingoes. Dingoes are also known to prey on kowaris at this time (Palmer 1999; authors' obs.). Therefore, the period following the boom is likely to be the time when populations of native fauna are most at risk from native and feral predators, particularly if the boom has elevated predator populations and the bust is severe, causing predators to be less risk averse. During this study, we did not find any evidence to suggest that dingoes on Diamantina helped conserve kowaris and their predation at the end of the boom likely contributed to the kowari's decline.

Kowari habitat and distribution

We found that the kowari's preferred habitat at Diamantina was the ironstone dominated plains with well vegetated drainage lines. Lim (1998) found that they used the drainage lines to hunt for food, for burrowing and for traversing the landscape. R. Brandle, P. D. Canty, L. Lim, unpubl. data, found that kowaris on Clifton Hills pastoral lease in South Australia preferred stony plains with more than 30% cover of pebbles, that were less than 50 mm in diameter, on a slope of less than 4°. In contrast, kowaris at Astrebla and in other parts of their range were regularly observed living on treeless clayey plains, with little to no vegetation cover, and with 20% or less stone cover (Lim 1992; authors' obs.).

Kowaris had a limited distribution on Diamantina relative to the abundance of ironstone and clayey/ashy downs/plains habitat. We found kowaris at 10 sites (9 km^2 mean home range), five of which were new and five of which were historical (prior to gazettal) (Lim 1992; C. Mitchell, QPWS, pers. comm., 2020). We did not find kowaris at one of the historical sites where the ironstone pebbles had been extracted for roadworks prior to it becoming a national park (C. Mitchell, QPWS, pers. comm., 2020). The new kowari sites suggest that the species has expanded its distribution since the national park was gazetted, but it may just be that the historical surveys were limited and opportunistic and the kowaris were missed. Despite our efforts to contact previous researchers and to search relevant databases, we are unable to determine the precise extent of the historical surveys, which included a combination of trapping and observational records (Lim 1993, 1998; C. Mitchell, QPWS, pers. comm.). Both the current and historical studies included dry and wet periods. The similar climatic conditions of the previous and current study confirms that the changes in the kowari distribution that were observed after gazettal are unlikely to be due to rainfall.

Kowari density

The highest densities of kowaris were found at Sites 2 and 5 in 2007 and 2008 (2–2.75 kowaris per km^2) which indicated that the population was doing well on Diamantina at the commencement of the study. The densities at Sites 4 and 11 were lower (1.0 kowaris per km^2). The latter density estimate was similar to those obtained from Clifton Hills Pastoral Lease in South Australia (1–1.6 kowaris per km^2) (Brandle *et al.* 2002). The low number of recaptures during our study meant that we were unable to estimate abundance and density for all sites. This was also a problem for Lim (1998) at one of his study sites. However, catching an adequate number of kowaris to estimate density at all sites would have required an enormous trap effort and no long-haired rat plague. Even with a vast increase in the number of traps or trap nights, the density of kowaris may be so low at some sites that it is not possible to robustly estimate density across all sites.

The value of long-term datasets and control sites

The combined results from our and Mitchell's (2022) long-term studies were valuable in assessing changes in the vegetation and they suggest that kowaris increased following a reduction in grazing pressure. However, despite the long-term dataset (15 years), the results are correlative. The occurrence of an unprecedentedly large boom followed by a severe bust over-rode any possible benefit of reduced grazing pressure. In this case, having a long-term dataset, which may in fact not be long at all in these arid systems, did not seem to compensate for the lack of a control site. Several authors have recommended that long-term monitoring, through a range of seasonal conditions be undertaken to improve our understanding of ecosystem change (Read 2002; Kraaij and Milton 2006; Pedler *et al*. 2016; Moseby *et al*. 2021; Piazza *et al*. 2021). Given that stray stock continue to graze the Park, correlative analysis is limited, and that further years of study will only reduce the uncertainty slowly, it would be more useful to establish a control site on a neighbouring cattle station to better evaluate trends in habitat condition and the kowari population. Finding a suitable control site is, however, very difficult in western Queensland due to the low density and distribution of the kowaris, the patchy rainfall, and the unpredictable boom– bust nature of the ecosystem.

The status of kowaris at Diamantina

The lack of any recent kowari sightings within the study area on Diamantina is cause for concern. Two other endangered species, the plains mouse and the dusky hopping-mouse, have also not been detected on the Park since 2000 (authors' obs.). Lim (1998) did not detect kowaris towards the end of his study, but animals subsequently recolonised the sites two years later. Given the large area impacted by the plague of long-haired rats in 2011 in and around Diamantina, the widespread abundance of predators, and that kowaris have not been detected within the study area in the last decade, it is likely that the declines have been widespread in western Queensland.

Conclusion

It is recommended that surveys within Diamantina be extended to include suitable habitat not previously assessed, particularly habitat further away from the Diamantina River, to better determine the status of kowaris on the Park. Kowari refugia may be areas with extensive ironstone and claypan pavements where predators are less abundant. Further studies are also required to determine whether off-park populations, particularly at Lim's (1998) Birdsville study site, were affected by the 2011 boom of resources and associated increased predation. If the off-park populations are similar to those at Diamantina then we strongly recommend that the species status be reassessed, and consideration be given to its eligibility for the 'endangered' category. Greenville *et al*. (2018) predicted a 20% chance of the species becoming extinct within the next 20 years.

Our study indicates that effective predator control will be critical to the recovery and maintenance of a kowari population on Diamantina. The ongoing measures to minimise cattle grazing will also be beneficial but are not as important as predator control. This study highlights the need for long-term, replicated studies with paired control sites if the interactions between complex ecological processes, at a landscape scale, and their effects on threatened species, like kowaris, are to be better understood and better managed.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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Appendix 1. The vegetation monitoring

Species composition, frequency and dominance

Ten 1 m × 1 m quadrats placed 5 m apart along the 50 m transect were used to assess understorey species composition. To avoid trampling, the first quadrat was placed at the 5 m point. The cover of each species present in the quadrat was recorded using the technique of Daubenmire (1959). A species was deemed to be present in a quadrat if it was rooted in the quadrat. A species was considered to be part of the understorey if it was herbaceous or was a woody plant no taller than 50 cm. Roots belonging to trees taller than a half a metre were classed as litter.

Foliage projective cover (FPC) of the understorey and soil disturbance

The point intercept technique at half metre intervals along each transect was used to assess FPC. The 'units' of cover were bare ground (separated into disturbed or not), rock, cryptogram crust, litter (detached organic material and dead organic material attached to a dead plant) and vegetation (including alive or dead material providing it is still attached to an alive plant).

Biomass

The dry weight of all alive and dead organic matter, up to a diameter of 5 mm, was collected, dried and weighed from five 50 cm × 50 cm quadrats. The location of each quadrat was random within an area of between 5 and 30 m from the transect line. Each sample was dried in the oven for 48 h at 70°C.

Site name	Site installation date	Easting	Northing
Davenport A	November-07	519 327	7 343 663
Davenport B	November-07	517 851	7 343 781
High Grid	October-08	518 650	7 365 501
Ironstone Knoll	November-07	520 750	7 355 600
Plains Bore	April-08	515 550	7 363 650
Senna Gully	April-08	518 685	7 366 356
Tulka Ironstone	May-06	518 670	7 344 230
Tulka Gypsum	May-06	518 562	7 344 543

(Datum GDA 94, UTM Zone 54).

Appendix 2. Kowari habitat search spotlight or thermal camera transects 2007–2021 (Ironstone habitat only). No surveys were conducted in 2016 or 2019

Year	Transect name	Transect length (km)
2007–2013	End of Cooyrie Sandhill to Middle Ck	7.8
2007–2013	South of Middle to Cooridy Ck	5.5
2007–2013	Cooridy Ck to Davenport	10.0
2008–2013	Plains Bore track	14.2
2015–2021	Bilby Paddock Western route	22.0
2014–2021	Bilby Paddock Eastern route	25.5
2014–2021	Senna Gully to Middle Ck	6.8

Appendix 3. Kowari predator/prey spotlight transects, 2007–2021. No surveys were conducted in 2016 or 2019

	Transect name	Distance (km)	Eastings	Northings
1	Homestead to Cooyrie Ck	4	514 394	7 371 903
			516 212	7 368 375
2	Cooyrie Ck to Middle Ck	10	516 172	7 368 426
			519 353	7 360 296
3	Middle Ck to Cooridy Ck	9	521 500	7 358 082
			521 114	7 352 947
4	Cooridy Ck to Davenport	10	520 788	7 352 161
			516 959	7 344 176
5	Plains Bore track (after October 2008)	17	513 902	7 363 900
			514 035	7 360 353

Appendix 4. Kowari trapping grid locations and the start and end point for each grid line in April 2007 and 2008

Grid name	Reference	Eastings	Northings
Senna Gully (Site 2)	SG1	519 338	7 365 966
	SG2	519 345	7 365 868
	SG3	519 343	7 365 775
	SG4	519 342	7 365 691
	SG5	519 341	7 365 631
	SG6	519 232	7 365 618
	SG7	519 146	7 365 631
	SG8	519 043	7 365 636
Plains Bore (Sites 3–4)	PB1	516 574	7 363 365
	PB2	516 540	7 363 274
	PB3	516 547	7 363 166
	PB4	516 528	7 363 063
	PB5	516 497	7 362 964
	PB6	516 414	7 362 905

(*Continued on next page*)

Grid name	Reference	Eastings	Northings
	PB7	516 305	7 362 892
	PB8	516 208	7 362 881
High Grid (Site 5)	HG1	518 007	7 364 463
	HG2	518 003	7 364 356
	HG3	518 087	7 364 304
	HG4	518 179	7 364 250
	HG5	518 270	7 364 202
	HG6	518 366	7 364 171
	HG7	518 466	7 364 163
	HG8	518 558	7 364 154
	IK1	520 748	7 355 591
	IK2	520 693	7 355 518
Ironstone Knoll (Site 8)	IK3	520 621	7 355 432
	IK4	520 569	7 355 347
	IK5	520 473	7 355 312
	IK6	520 369	7 355 324
	IK7	520 270	7 355 352
	IK8	520 173	7 355 357
Bilby North (Site 9)	BN1	519 339	7 351 601
	BN2	519 445	7 351 571
	BN3	519 545	7 351 536
	BN4	519 651	7 351 520
	BN5	519 743	7 351 500
	BN6	519 848	7 351 497
	BN7	519 930	7 351 437
	BN8	520 000	7 351 362
Bilby South (Site 11)	BS1	517 433	7 344 100
	BS2	517 516	7 344 188
	BS3	517 609	7 344 244
	BS4	517 703	7 344 282
	BS5	517 811	7 344 302
	BS6	517 893	7 344 343
	BS7	518 000	7 344 355
	BS8	518 104	7 344 335

(Datum GDA94, UTM Zone 54).

Appendix 5. Kowari search trapping sites, April and September 2007

Site name	Reference	Eastings	Northings	No. of traps
Lightning West	Start	532 584	7 365 825	40
	End	530 675	7 365 628	
Lightning East	Start	539 590	7 364 420	40
	End	540 960	7 363 053	

(*Continued on next page*)

Site name	Reference	Eastings	Northings	No. of traps
Plains Bore Rd	Start	513 820	7 362 936	40
	End	513 933	7 360 964	
Ironstone Knoll	Start	522 401	7 356 867	20
	End	523 022	7 356 186	
Scott's Tank track west	Start	524 128	7 355 906	40
	End	526 005	7 355 143	
Scott's Tank track east	Start	529 633	7 354 595	40
	End	531 512	7 354 191	
High Grid south	Start	518 913	7 361 910	80
Cooridy Ck Gravel Pit	Start	520 170	7 350 675	80
High Grid north	Start	518 143	7 366 491	80
Eight Mile	Start	520 081	7 383 046	40

Appendix 6. The number of individual Kowaris caught per survey for 2007–2012

Trip date and site name	No. of individuals	Recaptures	Total caught
Autumn 07	10	5	15
Bilby South Site (Site 11)	1	0	1
High Grid Site (Site 5)	8	5	13
Plains Bore Site (Site 4)	1	0	1
Spring 07	4	0	4
High Grid Site (Site 5)	2	0	2
Senna Gully Site (Site 2)	2	0	2
Autumn 08	14	4	18
Bilby South Site (Site 11)	1	0	1
High Grid Site (Site 5)	5	1	6
Plains Bore Site (Sites 3–4)	3	1	4
Senna Gully Site (Site 2)	5	2	7
Spring 08	4	0	4
Bilby South Site (Site 11)	1	0	1
Senna Gully Site (Site 2)	3	0	3
Autumn 09	9	1	10
Bilby South Site (Site 11)	3	1	4
High Grid Site (Site 5)	3	0	3
Plains Bore Site (Sites 3–4)	2	0	2
Senna Gully (Site 2)	1	0	1
Spring 09	10	1	11
Bilby South Site (Site 11)	4	0	4
High Grid Site (Site 5)	1	0	1
Plains Bore Site (Sites 3–4)	4	1	5
Senna Gully Site (Site 2)	1	0	1
Autumn 10	3	0	3
High Grid Site (Site 5)	2	0	2

(*Continued on next page*)

Trip date and site name	No. of individuals	Recaptures	Total caught
Plains Bore Site (Sites 3–4)	1	0	1
Autumn 11	3	0	3
Bilby South Site (Site 11)	2	0	2
High Grid Site (Site 5)	1	0	1
Spring 11	4	0	4
Plains Bore Site (Sites 3–4)	2	0	2
Senna Gully Site (Site 2)	2	0	2
Autumn 12	6	0	6
High Grid Site (Site 5)	5	0	5
Senna Gully Site (Site 2)	1	0	1
Grand Total	66	11	78

Appendix 7. Kowari numbers recorded during line transect surveys at the nearby Astrebla Downs National Park 2012–2021 (unpublished QPWS data)

Month	Distance travelled (km)	Kowari (minimum no. known to be alive)	Kowari/km
May-12	148	27	0.1824
June-12	410.7	26	0.0628
July-12	197	0	0.0000
August-12	70.5	0	0.0000
October-12	135.5	0	0.0000
March-13	85	3	0.0353
April-13	343	0	0.0000
May-13	868	0	0.0000
June-13	125	0	0.0000
July-13	673	0	0.0000
August-13	393	0	0.0000
September-13	169	0	0.0000
November-13	90	0	0.0000
April-14	85	1	0.0118
May-14[A]	936	4	0.0043
July-14	156.8	0	0.0000
September-14	216.2	4	0.0185
November-14	100	8	0.0800
February-15	200	2	0.0100
April-15[A]	350	10	0.0286
June-15	75	0	0.0000
September-15	91	0	0.0000
March-16	68	1	0.0147
May-16[A]	447	14	0.0480
August-16	484	1	0.0021
February-17	66	1	0.0152
March-17	60	1	0.0167
May-17	314	0	0.0000

(Continued on next page)

Month	Distance travelled (km)	Kowari (minimum no. known to be alive)	Kowari/km
July-17	60	0	0.0000
August-17[A]	266	2	0.0050
September-17	245.5	1	0.0041
November-17	250.1	3	0.0120
February-18	70	1	0.0143
May-18[A]	405	1	0.0025
July-18	96	0	0
September-18	415.2	1	0.0044
October-18	48	0	0
December-18	18	1	0.0556
January-19	0	0	0
May-19	503	5	0.0099
June-19[A]	199	11	0.0553
July-19	80	2	0.025
August-19	53	0	0
October-19	156	6	0.0873
May-20	308	4	0.009
June-20[A]	134	13	0.097
July-20	129.2	14	0.1084
October-20	143.1	12	0.0839
November-20	83.1	10	0.1203
January-21	15	1	0.0667
April-21	100	3	0.03
June-21[A]	64	14	0.2188

[A]Survey conducted using a thermal image camera.