

Supplementary material

This supplementary material relates to:

Title: Environmental effects are stronger than human effects on mammalian predator-prey relationships in arid Australian ecosystems

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Contents:

- Additional description of methods and results
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Additional description of methods (see also Table 2 in the main paper)

Do hopping-mice behave differently at times when dingoes are active or less-active?

Previous studies have suggested that hopping-mice forage more freely in the presence of dingoes (e.g. [Letnic and Dworjanyn 2011](#)). However, these conclusions have primarily been inferred indirectly from give-up densities associated with hopping-mice removal of seeds or boiled peanuts from feeding trays over a few nights only, and not from direct observations of hopping-mice behaviour (but see [Morris et al. 2015](#)). Thus, we first used the camera trap data (described in Section 2.5 of the main paper) to identify the timing of dingo and hopping-mice activity on roads (nocturnal, crepuscular etc). We then directly assessed actual hopping-mice behaviour by categorizing those observed in each photo as feeding, sitting, walking, running or hopping, interacting with other hopping-mice (e.g. mating or fighting), or indeterminate. Feeding, sitting and walking were considered collectively to represent ‘foraging’ behaviours. Next, we investigated the relationship between dingo activity (N dingoes observed per camera) and hopping-mice activity (N hopping-mice observed per camera) at the nightly scale, using simple linear regression. We further assessed whether or not hopping-mice behaved differently during hours of the night when dingoes were and were not detected on camera.

Do dingoes select sand dunes (preferred hopping-mice habitat) over swales, and are dingoes active on dunes during the times when hopping-mice are also active?

Habitat usage by dingoes was assessed in ArcGIS v9.3 (ESRI Inc.) by overlaying dingo location data from GPS collars over vector datasets of landform delineating dunes from swales – the only two habitat types at the study site. We first investigated the spatiotemporal use of sand dunes by dingoes in order to determine what time dingoes were active on dunes. Given that only two habitat types exist at the study site, we then used the log of the odds ratio to determine which habitat type was selected by dingoes between 18:00 and 06:00 (i.e. night time). This was calculated as:

$$\text{Habitat selection} = \log \frac{\left(\frac{Pd}{Pt - Pd} \right)}{\left(\frac{Ad}{At - Ad} \right)}$$

where Pt is the total number of nighttime points, Pd is the number of nighttime points on dunes, At is the total area of the study site (km^2) and Ad is the area of dunes (km^2). Using this approach, positive values denote preferential selection of sand dunes, whereas negative values would denote avoidance of sand dunes (or selection of swales). In other words, we assessed whether or not dingoes were selecting dunes during the time that hopping-mice were active on dunes.

What is the density of dingoes?

Dingo densities were determined by multiplying the number of dingo packs at the study site by dingo group sizes. The number and location of dingo packs was identified from the GPS collaring data (described in Section 2.6 of the main paper). Opportunistic observations of group size and reproductive output (or litter size) were combined with demographic data from 26 captured dingoes to yield information on pack demography (Table S1). Dingo densities are expressed as N dingoes/km².

Is hopping mice activity greater on dunes or swales?

Sand plot data (described in Section 2.4 of the main paper) were used to assess whether or not hopping-mice PTI was greater on dunes or swales in both treatments.

Are temporal trends in dingo and hopping-mice PTI similar between dingo-baited and unbaited areas, and is this result dependent on sampling in dunes or swales?

Lethal dingo control has been predicted to influence hopping-mice population trends ([Letnic et al. 2009](#); but see [Allen et al. 2014a](#)), but few studies have conducted more than a single snap-shot survey, or had the capacity to experimentally assess the actual responses of hopping-mice to dingo control ([Allen et al. 2013b](#)). Thus, sand plot data from our long-term experiment were used to assess whether or not PTI trends of dingoes and hopping-mice in both treatments were affected by sampling on dunes or swales.

Are dingo and hopping-mice activity levels consistent across the environmental gradient that extends from the centre of the desert to the edge of the desert, and is this dependent on sampling on dunes or swales?

Lower hopping-mice abundance in the east, or on the edge of the Strzelecki Desert has previously been attributed to the long-term effects of dingo removal associated with differing dingo abundances on either side of the dingo barrier fence (e.g. [Letnic et al. 2009](#); [Morris et al. 2015](#)). Plausible alternative explanations associated with cross-fence differences in historical and contemporary livestock grazing effects have been advanced ([Allen 2011](#)), but few studies have assessed the more fundamental bottom-up effects of geological resource (or dune) availability to hopping-mice (but see [Newsome et al. 2001](#)). An environmental gradient extends from the centre of the desert, where sand dunes are higher and closer together, to the edge of the desert, where sand dunes are lower and more widely dispersed ([Fitzsimmons 2007](#)). This environmental gradient can be easily observed using Google Earth. Sand plot data from the unbaited area (Coonee) was derived

from a transect which ran north-south (NS) for 25 km, and then ran east-west (EW) for the remaining ~25 km. Thus, the NS section of the transect was parallel to the edge of the desert in its centre, whereas the EW section of the transect was perpendicular to the edge of the desert and extended from the centre of the desert east towards its edge. This permitted an assessment of overall mean dingo and hopping mice PTI levels on each individual sand plot in both the NS and EW sections of the transect, using simple linear regression, which was undertaken separately for dunes and swales. By using data only from Coonee, all results of this analysis reflect bottom-up processes not influenced by lethal dingo control.

Is hopping-mice PTI lower closer to waterpoints in dingo-baited areas and higher closer to waterpoints in unbaited areas?

Previous studies have suggested that hopping-mice PTI is or should be lower around water points in areas where dingoes are baited, but not in unbaited areas ([Wallach and O'Neill 2009](#); [Brawata and Neeman 2011](#)). However, these studies have occurred over very short timeframes (just a few days; [Allen et al. 2013b](#)), and do not reflect longer-term relationships inclusive of the stochastic climatic variability that characterizes the arid zone. Thus, sand plot data was also used to assess overall mean dingo and hopping-mice PTI levels on each sand plot, at different distances away from water in baited (Finlay) and unbaited (Coonee) areas, and on both dunes and swales, using simple linear regression.

Do single-survey studies show hopping-mice PTI to be positively correlated with dingo PTI at fine scales (i.e. at the sand plot level)?

Snap-shot or single-survey correlative studies commonly yield different results to longer-term and/or experimental ecological studies (e.g. [Thompson 2004](#); [Fairweather and Quinn 2006](#); [Banks-Leite et al. 2011](#); [Hamel et al. 2013](#)). Thus, we used our long-term and experimental sand plot data (described in Section 2.4 in the main paper) to calculate PTI of dingoes and hopping-mice at each sand plot, in each treatment, during each survey, similar to the approach used by others in previous studies. Dingo PTI values for each sand plot were compared to hopping-mice PTI values to investigate whether or not dingo PTI correlated with hopping-mice PTI at fine spatial scales (i.e. at the sand plot level). Simple linear regression was used to assess the relationship between dingoes and hopping-mice for all significantly positive or negative correlations.

How common are hopping-mice in dingo scats?

We used dingo scat data (described in Section 2.7 of the main paper) to assess the percent occurrence of hopping-mice remains in dingo scats, both overall and separately for each survey and treatment.

Are hopping-mice always consumed along with other mammalian prey?

From the total sample of dingo scats collected, we first identified the scats that contained hopping-mice remains. We then investigated the presence of additional species in these scats. Where multiple species were identified, we ordered them in terms of volume to determine which prey species formed the most important component of the scat.

Do hopping-mice feature in dingo diets consistently, or only when preferred dingo prey (rabbits) are unavailable?

Dingo scat data were used in a simple linear regression to assess dingo prey switching between primary and secondary prey when primary prey were unavailable (or the substitution of rabbits for hopping-mice), separately for both dingo-baited and unbaited areas. We considered the results of each scat survey to be independent for this analysis.

Are hopping-mice consumed by dingoes in proportion to their availability?

To investigate the functional relationship between dingoes and their prey, we plotted the percent occurrence of hopping-mice in dingo scats against hopping-mice PTI trends in both dingo-baited and unbaited areas. Our primary aim was to determine how the occurrence of hopping-mice in dingo scats changed in response to fluctuations in prey availability, or PTI. An increasing percent occurrence of hopping-mice remains in dingo scats during a period of decreasing hopping-mice availability or PTI would be indicative of a serious potential threat of dingoes to hopping-mice populations ([Sinclair et al. 1998](#); [Allen and Leung 2012](#)).

Are hopping-mice population trends related to cattle densities?

Livestock grazing has been identified as a potential threat to small mammals through competition and trampling ([McKenzie et al. 2007](#); [Fensham and Fairfax 2008](#); [Smyth et al. 2009](#); [Kutt and Gordon 2012](#)). Thus, in order to assess the potential for cattle grazing to influence hopping-mice activity trends, background data on cattle density (N cattle per waterpoint) at each sub-site were obtained regularly throughout the study at cattle mustering times using automated cattle-counting technology installed at each cattle-handling yard within each treatment. Linear regression was used to explore relationships between cattle density and hopping-mice activity.

Additional description of results (see also Table 2 in the main paper)

Passive tracking index (PTI) surveys were undertaken on 16 occasions between April 2008 and May 2012 (see also [Allen et al. 2013a](#); [Allen et al. 2014a](#)). During these surveys, we recorded a total of 1,924 dingo intrusions or tracks (N = 720 in dingo-baited areas, and N = 1,204 in unbaited areas) and 18,619 hopping-mice tracks (N = 7,990 in dingo-baited areas, and N = 10,629 in unbaited areas).

Camera trapping yielded a total of 6,828 photos (N = 4,168 in dingo-baited areas, and N = 2,660 in unbaited areas), which included 1,122 photos containing hopping-mice (N = 865 in dingo-baited areas, and N = 257 in unbaited areas). Of the 1,122 photos containing hopping-mice (e.g. Plate S3), individual hopping-mice were photographed on 1,196 occasions in dingo-baited areas, and 272 occasions in unbaited areas (N = 1,468 in total).

The GPS collars deployed on dingoes yielded a total of 115,622 GPS points (Table S1); 70,788 were recorded during the day, and 52,078 were recorded during the night. A total of 32,105 GPS points were recorded on sand dunes during the night. Mean HDOP values ranged between 1.6 and 1.9 for each collared dingo (overall mean HDOP = 1.7), indicating excellent accuracy of the GPS points we obtained ([Allen et al. 2014b](#)).

We collected dingo scats on 14 occasions between May 2008 and May 2012, which yielded a total of 2,571 scats (N = 1,101 in dingo-baited areas, and N = 1,470 in unbaited areas; see also [Allen 2012b](#)). A total of 17 different food items were identified in these dingo scats, which primarily consisted of rabbits, hopping-mice, invertebrates and vegetation (Table S2; see also [Allen and Leung 2012](#); [Allen and Leung 2014](#)).

Do hopping-mice behave differently at times when dingoes are active or less-active?

See Section 3.1 in the main paper.

Do dingoes select sand dunes (preferred hopping-mice habitat) over swales, and are dingoes active on dunes during the times when hopping-mice are also active?

Approximately 39.9% of the unbaited area (Coonee) was classified as sand dunes, whereas approximately only 29.3% of the baited area (Finlay) was classified as sand dunes (see also [Fitzsimmons 2007](#)). A mean of 28.7% (N = 17, range = 15.9% to 39.0%) of GPS points from collared dingoes were located on sand dunes during the night. The log odds of a dingo being present on a sand dune (and not a swale) between 18:00 and 06:00 ranged between 0.09 and 1.19 (mean = 0.54, N = 17).

What is the density of dingoes?

Dingoes from 11 separate packs or territories were collared. The home range sizes of resident or non-dispersing dingoes were each approximately 25 km² (Table S1), and were arranged around shared water points like petals on a flower (see also [Allen 2012a](#)). The largest group size observed on any occasion was 12, comprising six adults and six sub-adults or yearlings (see also [Allen 2010](#)). Combined with the demographic data associated with each captured dingo (Table S1) and knowledge of typical dingo group structures ([Corbett 2001](#); [Fleming et al. 2001](#); [Purcell 2010](#)), we estimated dingo density at the site to be 0.4 dingoes/km², or approximately 10 dingoes (on average) for each typical 25 km² home-range area.

Is hopping mice activity greater on dunes or swales?

Hopping-mice were detected on both dunes and swales in both drought and flush periods (Fig. 2, Table S3). Mean hopping-mice PTI was higher on dunes at all times (range 9–93% higher on dunes), with differences demonstrable for both Coonee ($t = 5.2560$, $df = 15$, $p = 0.0001$) and Finlay ($t = 1.9268$; $df = 15$, $p = 0.0732$). During drought conditions only, hopping-mice PTI was 46% higher on sand dunes than swales in the baited area (Finlay), and was 93% higher on sand dunes than swales in the unbaited area (Coonee). This difference was less pronounced during flush conditions when hopping-mice were superabundant, when hopping-mice PTI was 9% higher on dunes than swales in the baited area and 23% higher on dunes than swales in the unbaited area. Across all surveys ($N = 16$), hopping-mice PTI was 14% higher on dunes than swales in the baited area and 39% higher on dunes than swales in the unbaited area (Table S3).

Are temporal trends in dingo and hopping-mice PTI similar between dingo-baited and unbaited areas, and is this result dependent on sampling in dunes or swales?

PTI trends of hopping-mice in both treatments declined to near-undetectable levels in December 2009 before subsequent and rapid rainfall-induced increases to peaks in 2011 and 2012 (Fig. 2), when sand plots were often saturated with hopping-mice tracks. Dingo PTI followed similar trends, but with a ~12 month lag behind their prey. These trends were evident regardless of whether or not sampling occurred on sand dunes or swales; the results from sampling in these two habitats exhibited a high degree of parallelism in temporal fluctuations of PTI trends for hopping-mice ($r = 0.9461$, $df = 15$, $p < 0.0001$) and dingoes ($r = 0.6142$, $df = 15$, $p = 0.0114$; see also [Allen et al. 2013a](#); [Allen et al. 2014a](#)) over the study period, in both Coonee and Finlay (Fig. 2). Thus, PTI trends for both species fluctuated independently of treatment and were therefore influenced to a much greater

extent by bottom-up factors (e.g. rainfall) than top-down factors (e.g. lethal dingo control, or baiting).

Are dingo and hopping-mice activity levels consistent across the environmental gradient that extends from the centre of the desert to the edge of the desert, and is this dependent on sampling on dunes or swales?

Overall dingo and hopping-mice PTI declined along the environment gradient from west to east (Fig. 3). Deconstructing this result (Table S4, Fig. S4) indicated that PTI declines were detectable only in swales and only on the east-west section of the transect, for both dingoes ($r = -0.5695$, $df = 15$, $p = 0.0213$) and hopping-mice ($r = -0.4715$, $df = 15$, $p = 0.0652$). In other words, in the north-south section of the transect neither dingoes nor hopping-mice declined on either dunes or swales. Whereas, both species declined in the east-west section of the transect, which decline was influenced primarily by reduced PTI in swales (i.e. PTI remained relatively unchanged along dunes, but declined in the swales as the nearby dunes became lower in height and further apart; Fig. S4, see also [Fitzsimmons 2007](#)).

Is hopping-mice PTI lower closer to waterpoints in dingo-baited areas and higher closer to waterpoints in unbaited areas?

See Section 3.2 of the main paper.

Do single-survey studies show hopping-mice PTI to be positively correlated with dingo PTI at fine scales (i.e. at the sand plot level)?

See Section 3.2 of the main paper.

How common are hopping-mice in dingo scats?

Remains of hopping-mice were found in 285 of 2,571 dingo scats (11.1% occurrence overall) over the entire study period. For any given survey, the percent occurrence of hopping-mice in dingo scats ranged between 2% ($N = 48$) in Coonee in September 2009 to 64% ($N = 14$) at the same sub-site in August 2011, and might be considered secondary prey for dingoes. Relatively low sample sizes in the post-rainfall period might weaken the precision of these averages; however, when averaged across all post-rainfall surveys since September 2010 in both sub-sites, hopping-mice occurred in 30% (93 of 310 scats) of dingo scats. This result is also substantially higher than results from any previous survey in the pre-rainfall period (Fig. 6), suggesting that the results from individual surveys undertaken in the post-rainfall period are robust despite small sample sizes.

Are hopping-mice always consumed along with other mammalian prey?

Of the dingo scats containing hopping-mice, approximately two-thirds contained hopping-mice as the sole mammalian prey item, suggesting that dingoes can meet their energetic requirements by consuming only rodents ([Carbone et al. 1999](#); [Allen and Leung 2012](#)).

Do hopping-mice feature in dingo diets consistently, or only when preferred dingo prey (rabbits) are unavailable?

See Section 3.3 of the main paper.

Are hopping-mice consumed by dingoes in proportion to their availability?

See Section 3.3 of the main paper.

Are hopping-mice population trends related to cattle densities?

Hopping-mice PTI showed no relationships with cattle density in both Finlay ($r = 0.4112$, $df = 8$, $p = 0.2715$) and Coonee ($r = 0.5511$, $df = 8$, $p = 0.1241$), or in both areas combined ($r = 0.5734$, $df = 8$, $p = 0.1065$). Mean cattle densities at Finlay (529 cattle per waterpoint) and Coonee (495 cattle per waterpoint) between January 2007 and June 2010 were similar at each sub-site ($t = -0.2114$, $df = 75$, $p = 0.8331$). However, routine cattle movement and handling practices meant that relatively large numbers of cattle were temporarily held (i.e. for a few days) at waterpoints before subsequent mustering and sale, giving the mistaken impression of higher-than-normal cattle densities. In practice, approximately 250–300 cattle per waterpoint were grazed under average conditions in both sub-sites. The median number of cattle per water point was 256 for Coonee and 275 for Finlay. Due to drought, Finlay was destocked in October 2009 and remained free of cattle until March 2013. Cattle numbers in Coonee were reduced to <100 by November 2009, and were removed completely in late 2010. No cattle were present in Coonee for the remainder of this study.

Plates



Plate S1 – Typical landscapes and vegetation conditions at Quinyambie during the course of the study.



Plate S2 – A typical passive tracking plot or sand plot, as viewed from a trail camera.



Plate S3 – Dusky hopping-mice (*Notomys fuscus*) exhibiting a variety of behaviours on camera (e.g. bottom left = walking; bottom centre = running/hopping; all others = sitting or feeding).

Tables

Table S1 – Details of collared dingoes.

Sub-site (treatment)	DogID	Capture date	Estimated age (mths)	Sex	Weight (kg)	GPS points obtained (% of expected points)	Days monitored	95%MCP (km ²)	Notes
Coonee (unbaited)	Dog01	11-Nov-08	28	M	23	9353 (72.2%)	270	21.3	
	Dog02	11-Nov-08	28	M	23	3197 (88.8%)	75	24.9	
	Dog03	11-Nov-08	16	F	13	3758 (86.0%)	91	19.3	
	Dog04	11-Nov-08	28	M	19	10870 (83.9%)	270	1249.2	
	n/a	11-Nov-08	28	M	21	*	*	*	Euthanased (trap-related injuries)
	Dog05	11-Nov-08	28	F	15	2856 (73.5%)	81	13.6	
	Dog06	11-Nov-08	16	F	15	4791 (75.0%)	133	31.3	
	Dog07	12-Nov-08	4	M	10	7 (14.6%)	1	*	Slipped collar
	Dog08	12-Nov-08	64	M	22	153 (63.8%)	5	*	Slipped collar
	Dog09	12-Nov-08	64	F	15	2656 (65.9%)	84	23.3	
	Dog10	12-Nov-08	28	M	19	11897 (92.8%)	267	98.2	
	Dog11	12-Nov-08	28	M	19	743 (86.0%)	18	29.0	
n/a	12-Nov-08	28	M	19	*	*	*	Euthanased (surplus to requirements)	
Finlay (baited)	Dog17	04-May-11	22	M	17	11505 (81.3%)	295	44.2	
	Dog18	04-May-11	22	F	13	8724 (69.1%)	263	40.9	
	Dog19Q	04-May-11	22	M	18	2038 (98.7%)	43	110.1	
	Dog20	04-May-11	22	F	15	*	*	*	Collar and data not recovered
	Dog21Q	05-May-11	22	F	13	8790 (87.6%)	209	24.5	
	Dog22	05-May-11	22	M	19	*	*	*	Data corrupted and unusable
	Dog23	05-May-11	34	F	15	5274 (83.9%)	131	39.4	
	Dog24Q	05-May-11	22	M	19	8215 (61.8%)	277	21.0	
	Dog25	05-May-11	22	M	19	*	*	*	Collar and data not recovered
	Fox	05-May-11	Adult	M	5	*	*	*	Non-target species (released uncollared)
	Dog26	06-May-11	22	F	14	*	*	*	Collar and data not recovered
	Dog27	06-May-11	22	F	13	*	*	*	Data corrupted and unusable
	Dog28	06-May-11	10	M	15	9087 (88.1%)	215	672.5	
Dog29	06-May-11	10	F	14	11868 (84.4%)	293	45.9		

Table S2 – The number (and proportion) of 17 food items detected in 2,571 dingo scats from Quinyambie during the course of the study, identifying a selection of the fauna present at the site (see also [Allen and Leung 2012](#) and [Allen and Leung 2014](#)).

Food item	Finlay	Coonee
N =	1101	1470
<i>Bos taurus</i>	80 (0.07)	82 (0.06)
<i>C. l. dingo</i> (prey)	6 (0.01)	12 (0.01)
<i>Felis catus</i>	1 (0.00)	4 (0.00)
<i>Macropus rufus</i>	39 (0.04)	4 (0.00)
<i>Nyctophilus geoffroyi</i>	1 (0.00)	0 (0.00)
<i>Mus musculus</i>	13 (0.01)	39 (0.03)
<i>Notomys fuscus</i>	98 (0.09)	187 (0.13)
<i>Oryctolagus cuniculus</i>	811 (0.74)	1103 (0.75)
<i>Pseudomys hermannsburgensis</i>	1 (0.00)	1 (0.00)
<i>Pseudomys australis</i>	0 (0.00)	1 (0.00)
<i>Rattus villosissimus</i>	7 (0.01)	43 (0.03)
<i>Sminthopsis crassicaudata</i>	2 (0.00)	0 (0.00)
<i>Sminthopsis macroura</i>	14 (0.01)	10 (0.01)
Invertebrates	199 (0.18)	133 (0.09)
Vegetation	183 (0.17)	232 (0.16)
Birds	53 (0.05)	59 (0.04)
Reptiles	64 (0.06)	38 (0.03)

Table S3 – Percentage difference in hopping-mice activity between sand dunes and swales in Finlay and Coonee during drought and flush seasonal conditions. Positive values denote greater activity on sand dunes.

	Drought	Flush	Overall
Finlay	46%	9%	14%
Coonee	93%	23%	39%

Table S4 – Effects of transect orientation (east-west or north-south) and habitat (dunes or swales) on the spatial distribution of overall mean dingo and hopping-mice PTI in the unbaited treatment area, 2008–2012.

	Transect	Habitat	r	df	p
Dingoes	east-west	dunes	-0.2959	8	0.4394
		swales	-0.5695	15	0.0213
	north-south	dunes	-0.2527	14	0.3636
		swales	-0.0159	9	0.9653
Hopping-mice	east-west	dunes	-0.3833	8	0.3086
		swales	-0.4715	15	0.0652
	north-south	dunes	0.0987	14	0.7264
		swales	-0.3837	9	0.2737

Figures

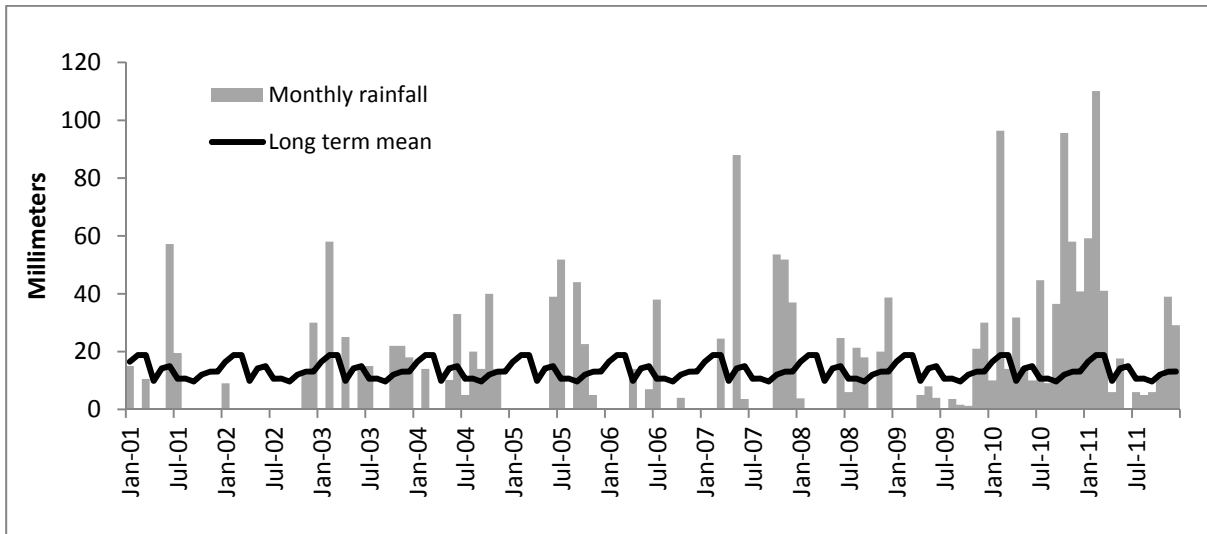


Fig. S1 – Monthly rainfall trends at Quinyambie, 2001–2012.

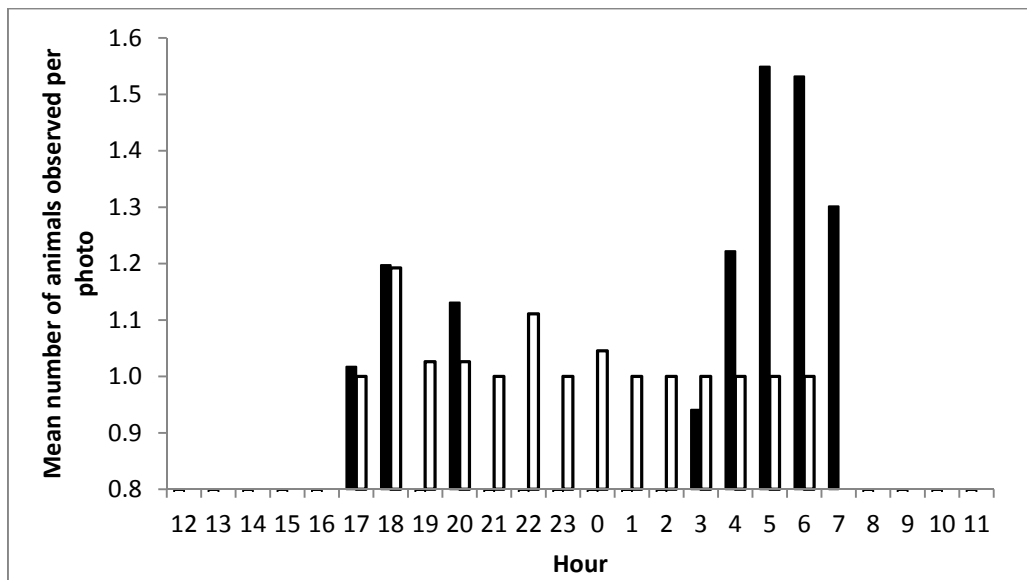


Fig. S2 – Dingo (solid bars) and hopping-mice (hollow bars) activity levels on 10 remote cameras in the unbaited area (Coonee), 10 June to 11 July 2011.

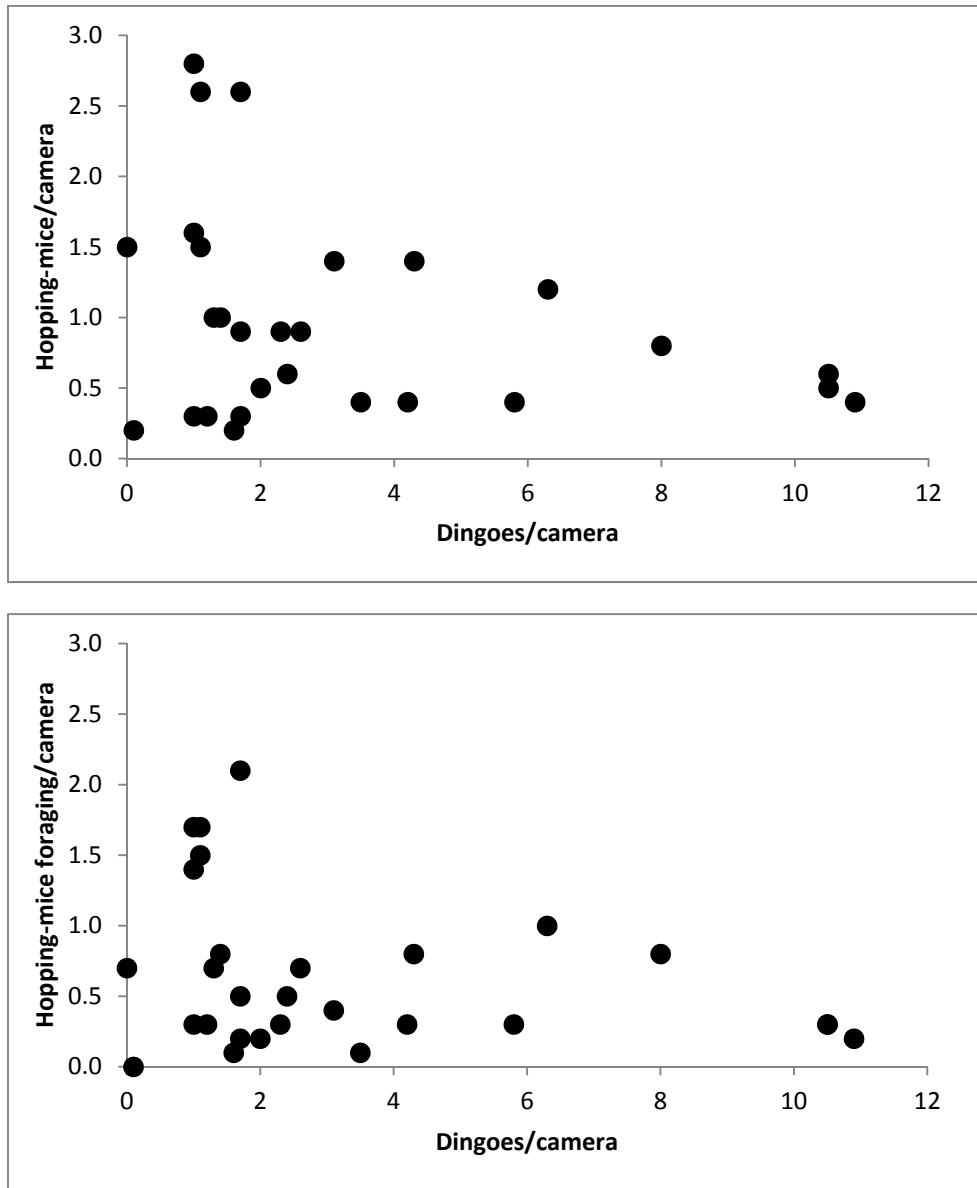


Fig. S3 – The relationship between dingo activity and hopping-mice activity on camera (top), and the relationship between dingo activity and hopping-mice foraging behaviour (bottom).

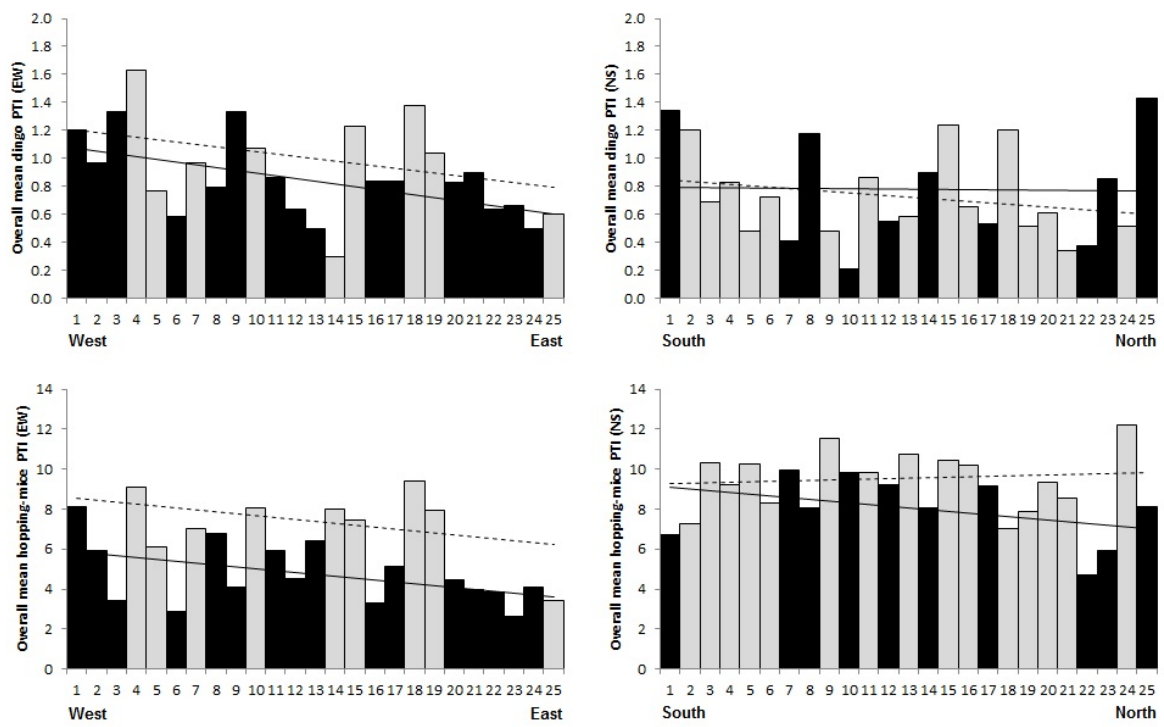


Fig. S4 – Spatial distribution of PTI trends for dingoes (top) and hopping-mice (bottom) in the unbaited area (Coonee), 2008–2012, on sand dunes (grey bars, dashed lines) and swales (black bars, solid lines) in the east-west section of the transect (left) and the north-south section of the transect (right).

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