Influences of adjacent suburbia, fire regimes, vegetation and environment on the mammals of a peri-urban reserve

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Abstract

Urban development is thought to negatively affect most, but not all, native mammals. Here we determine whether adjacent suburbia, fire regime, vegetation and environment affect the abundance of mammal species in a peri-urban reserve in Hobart, Tasmania, Australia. We used multiple regression to analyse the effects of distance from houses, variation in fire history, vegetation structure, vegetation floristics and topography on mammal photographic observations and signs. Animal diggings, long-nosed potoroos, southern brown bandicoots and cats were preferentially found close to houses, while macropods, brushtail possums and short-beaked echidnas appeared indifferent to the location of housing but responded to environmental variation. The structure of the vegetation, particularly related to shelter, was a strong influence in many species' models, suggesting a need to maintain substantial areas free from fire for 15–25 years. Many models included floristic ordination axes that reflected drainage, fire regime and proximity to housing. Positive relationships between the introduced predatory cat and some of its potential native prey animals may reflect the influences of close proximity to suburbia: elevated domestic mesopredator populations; and, elevated resource availability in domestic gardens. Our results suggest that urban areas can have a valuable role in nature conservation, despite, or because of, their effects on remnant native ecosystems. Planning and management can help promote populations of many native mammals.

Introduction

Urbanisation is rapidly expanding and is one of the leading causes of global biodiversity loss and species extinction (Czech et al. 2000; Marzluff 2001; McKinney 2006). It can impact species through a range of processes including: loss, degradation and fragmentation of natural habitats; increases in exotic species, noise and light pollution; and altered hydrology. Impacts vary depending on the degree of urbanisation (McKinney 2002; McKinney 2008). Urban areas, particularly suburban areas, often contain remnant patches of seminatural habitats, parklands, sports fields and substantial areas of private residential gardens (green spaces), which provide habitats for a range of species and may be important for species conservation. For example, the nationally threatened eastern barred bandicoot (*Perameles gunnii*) is more common in exurban developed environments near Hobart than in equivalent native vegetation (Daniels and Kirkpatrick 2012). In a review of 787 papers, Shwartz et al. (2014) found that the importance of urban areas for general conservation is not convincingly supported by empirical research, with only a few studies showing these areas can support viable populations of rare or endangered species. Some studies (summarised in McKinney 2002) have reported higher species richness in some suburban areas than in more natural areas, a pattern consistent with the intermediate disturbance hypothesis. Suburbs in a matrix of largely natural habitat may provide environmental heterogeneity, which is further enhanced by productive suburban gardens (Falk 1976; McKinney 2002). However, other studies have reported reduced species diversity in suburban and exurban areas (Marzluff 2001; Daniels and Kirkpatrick 2012).

Globally most urban conservation studies have focussed on plants, invertebrate and birds (Shwartz et al. 2014). In Australia, there have been few studies involving mammals. Tait et al. (2005) found that fifty percent of the native mammal species were lost from Adelaide, South Australia between 1836, when it was founded, and 2002. Habitat structure, rather than vegetation composition, was found to be most important for determining small mammal species assemblages in remnant urban habitat fragments of Brisbane City, southeast Queensland (Garden et al. 2007). In the same region, Brady et al. (2011) found that native mammal species richness peaked at moderate levels of development intensity. Daniels and Kirkpatrick (2012) found that exurban areas lacked mammal species found in equivalent wildlands but had higher frequencies of the endangered eastern barred bandicoot. Bryant et al. (2017) reported that the presence of quenda (*Isoodon fusciventer*) diggings in 106 reserves managed by the City of Mandurah, Western Australia was positively correlated with vegetation extent and negatively correlated with access to reserves by domestic dogs. A questionnaire survey of urban residents of southwestern Australia by Van Helden et al. (2020) reported that residential gardens offer a valuable habitat for mammals, and that garden features such as vegetation cover could be manipulated to promote the use of gardens by species such as brushtail possum (*Trichosurus vulpecula*), western ringtail possum (*Pseudocheirus occidentalis*) and the quenda .

With rates of urbanisation increasing globally there is a need to better understand factors that could help maintain and promote retention of native species and mitigate against negative factors. This is particularly required where large remnants of native vegetation occur adjacent to, or enclosed by, urban development. Fire and weed management can be difficult if maintenance of native mammal biodiversity is a primary aim. Fires imposed to protect nearby housing and arsonists' fires can deleteriously affect habitats for mammals if undertaken too frequently or if not enough unburnt habitat is retained. Weeds are difficult to eradicate because of heightened fertility from air pollution and waste and the propagule load from gardens (Ivey-Law and Kirkpatrick 2016). Yet there are indications in Australian literature that there can be positive effects of weeds on at least some native mammals. For example, a common weed in temperate peri-urban areas, European gorse (*Ulex europaeus*), provides protection for many native mammals (Driessen et al. 1996; Mallick et al. 1997; Low 2002; Ranyard et al. 2018).

Understanding the importance of urban areas for biodiversity conservation is context dependent because density of housing, area and distribution of green spaces and native vegetation, as well as other factors can vary considerably between urban landscapes. Here, we investigated the effects of proximity to housing, hazard reduction burning and exotic species on the activity of native mammals in an adjacent native bushland reserve, accounting for vegetation structure, vegetation floristics and topography.

Methods

Study area

The study was conducted in a small conservation reserve (Peter Murrell State Reserve and Conservation Area; 277 ha; 43°00' S, 147°18' E) comprising eucalypt forest, eucalypt woodland (mainly black peppermint *Eucalyptus amygdalina*) and heath that is isolated from other areas of native vegetation by development, including adjacent residential suburbs (Fig. 1). The study area is described in detail by Kirkpatrick (1999) and Driessen et al. (2010).

Experimental design

This study used a design established to investigate the response of mammal activity to planned burns, comprising four fire management blocks (each 17–20 ha), two scheduled for planned burns and two to remain unburnt (Driessen and Jarman 2010; Driessen and Jarman 2014; Driessen et al. in press). Two transects, 100 m apart, were established in each block and each transect consisted of 10 sampling stations each 50 m apart (Fig. 1).

Data collection

Camera-trapping took place in seven-day sessions at four sampling stations per transect (total 32 sampling stations) in autumn and spring 2018. KeepGuard KG 680V cameras were attached to small trees, 0.5–1 m above the ground, and facing a PVC container of bait (peanut butter, rolled oats and sesame oil) pegged into the ground 1–2 m away. Cameras, with a minimum triggering interval of 30 s, took single-frame images, with date and time recorded on each. All images were assessed for the presence of an animal and in most images the species was identified. Our metric for mammal activity was the number of visits by a species rather than the number of images (Jarman and Driessen 2019). We defined a visit as one or more images of a species with no interval between animal images greater than 5 min. Our choice of 5 min as the maximum allowable within-visit interval was based on our analyses of inter-image durations in large samples of timed images of long-nosed potoroos (*Potorous tridactylus*) (Jarman and Driessen 2019) and was appropriate for other species recorded in the study area (P. Jarman and M. Driessen, unpublished data).

In Autumn 2018, all observed vascular plant taxa were recorded in 80 10-by-10 m plots centred on the trap stations. The tape that defined the borders of each plot was used as an intercept line. The outline intercept cover was measured to the nearest cm for shrubs, graminoids (all monocotyledonous plants), ferns, herbs, bryophytes, lichen, bare ground (clear to the sky), rock and litter. A Bitterlich wedge count from the middle of the quadrat was undertaken by species to determine basal area. Slope (degrees), aspect (degrees) and topographic position (lower, upper, ridge and valley) were also recorded. The distance in metres to the nearest house and the nearest high-density housing (250–1000 houses/km^2) was calculated using Google maps. Each of macropod (Bennett's wallaby (*Notamacropus rufogriseus*) and rufous-bellied pademelon (*Thylogale billardierii*)), possum (brush-tail (*Trichosurus vulpecula*) and ring-tailed (*Pseudocheirus peregrinus*)) and European rabbit (*Oryctolagus cuniculus*) scats were counted for the whole plot, as were all marsupial and monotreme diggings.

In autumn 2018, an index of horizontal vegetation density was recorded for all stations using a 100-cm-tall by 50-cm-wide board marked with 200 5-by-5-cm squares. The board was placed on the ground 5 m to the north, and then to the south, of each trap station and the numbers of squares obscured by vegetation between 0 and 50 cm and between 50 and 100 cm above the ground were recorded by an observer standing at the trap station. The average of the north and south scores provided an index for the trap station of vegetation density between 0 and 50 cm and between 50 and 100 cm.

Fire history data since 1988 was obtained from the Peter Murrell State Reserve and Conservation Area Fire Management Plan (PWS 2006) as well as a fire mapping database maintained by the Tasmanian Parks and Wildlife Service. From this information the times since last fire in 2018, and number of fires between 1988 and 2018 were determined for each station.

Statistical analysis

All analyses were undertaken in Minitab18, except for ordination of the vegetation data. The non-metric global multidimensional scaling ordination of the plant species presence/absence data used the default options in DECODA.

By testing relationships, rather than central tendencies, we attempted to mitigate the non-random nature of the experimental design. Where possible, our analyses remove colinearities from predictive equations. However, the precision of measurement can affect the relative strength of explanatory variables, thereby influencing inclusion, so we have been careful to assess the logic of the variables included in our models.

Chi^2 was used to determine the significance of relationships between class variables. Cat and short-beaked echidna (*Tachyglossus aculeatus*) photographic trappings were too infrequent to treat as continuous variables, so were treated as presence/absence. One-way ANOVA was used to determine whether animal observations and some environmental variables varied by the time since the last fire, the presence/absence of cats and the presence/absence of echidnas. Pearson product moment correlation coefficient was used to determine the significance of linear relationships between continuous variables.

Multiple regression analysis, guided by the 'Best Subsets' routine in Minitab, was undertaken with each of the taxa, and indicators of taxa, for which quantitative data were available as dependent variables. Predictor variables are detailed in Table 1. The maximum number of predictor variables was determined by the sample size, with at least 10 samples per variable being used to avoid overfitting. The selected best model was that which had the highest adjusted r^2 and significant ($P < 0.05$) slopes on each variable.

Results

Variation in vegetation and its correlates

The four-dimensional ordination solutions had a minimum stress of 13.4%. The first axis discriminated assemblages of dry heathy vegetation, characterised by such species as *Bossiaea cinerea*, *Allocasuarina monilifera* and *Epacris impressa*, from other types of assemblages (Table 2). The heathy extreme was on steeper slopes (Table 3).

The second axis discriminated species assemblages characteristic of heaths on poorly-drained ground from the rest. The species of poorly-drained ground included *Gymnoschoenus sphaerocephalus,* *Leptocarpus tenax* and *Restio monocephalus* (Table 2). The scores on this axis were also predicted by slope, with the positive values associated with species of the poorly-drained ground associated with gentler slopes (Table 3).

The scores on axis 3 were strongly correlated with graminoid cover, with high cover of *Gahnia radula* and *Hypolaena fastigiata* at the positive end of the axis. (Table 2). The scores on this axis were also correlated with the two distance-from-house variables (Table 3).

The scores on the fourth axis discriminated recently burned vegetation from less recently burned vegetation, with strong correlations with time since last fire and number of fires, as well as distance from dense housing (Table 3). Variation in bare ground was associated with the axis scores (Table 3).

Predictive models for diggings, scats and taxa

Total diggings were predicted by both southern brown bandicoot (*Isoodon obesulus*) visits (r = 0.496, d.f. = 30, P = 0.004) and echidna visits (r = 0.472, d.f. = 30, P = 0.006). In the best environmental model, total diggings increased in density with increasing time since last fire, increasing basal area of *Eucalyptus amygdalina* and increasing slope; species richness became higher and decreased as vegetation 50–100 cm in height became denser; the score on axis 4 of the ordination became greater, indicating no recent fire; and the distance to high-density housing became greater (0.88 + 0.537 Euca amBW + 0.572 spec rich - 16.1 MDS AXIS 4 4 - 0.154 Density(0–50cm) + 0.497 YearsSinceLastFire - 0.00950 DISTD + 0.799 Slope, r^2 = 47.4%).

In the best regression model, long-nosed potoroo visits were associated with nearby high-density housing, high shrub cover and scores on ordination axis 2 that indicated good drainage (27.7 - 0.0159 DISTD + 0.149 Shr cove - 9.68 MDS AXIS 4 2, r^2 = 44.5%).

Southern brown bandicoot visits tended to occur near high-density houses in black peppermint forest that had not been burned recently, but which had been burned a high number of times (- 42.4 - 0.00605 DISTD + 0.178 Euca amBW + 0.885 YearsSinceLastFire + 20.3 NoOfFires, r^2 = 73.5%).

Bennett's wallaby visits were positively correlated with macropod scat density (r = 0.564, d.f. = 30, P = 0.001). Total diggings had a negative relationship with macropod scat density (r = - 0.291, d.f. = 78, P = 0.009). In the best model, macropod scats increased in density with increasing graminoid cover, decreasing time since last fire and decreasing black peppermint basal area (263 - 11.3 Euca amBW + 3.77 Gram cove - 8.45 YearsSinceLastFire, r^2 = 45.8%).

The best model indicated that Bennett's wallaby avoided dense ferns, but preferred vegetation that was dense between 50 and 100 cm height and that wallabies were more likely to visit stations where fire was recent (6.60 - 0.100 Fern cover + 0.113 Density(50–100) - 0.199 YearsSinceLastFire, r^2 = 34.3%). The best predictor for rufous-bellied pademelon visits was the density of foliage between 50 and 100 cm in height

(11.4 + 0.599 Density(50–100), r^2 = 39.2%). The denser the foliage at this height above the ground the more visits of pademelons were recorded.

Brushtail possum scat density was best, but weakly, predicted by total basal area (- 2.41 + 0.468 Tot BW, r^2 = 6.1%). The best model for brushtail possum visits indicated that they most often occurred in places with low fern cover and with low scores on the fourth floristic axis, indicating recent fire (8.88 - 0.0984 Fern cover - 8.41 MDS AXIS 4 4, r^2 = 44.5%).

Cat visits occurred closer to high-density housing (cat present mean distance to high-density housing = 380 m, cat absent mean = 765 m, $F = 17.81_{1,30}$, $P < 0.001$). The places they visited had lower graminoid cover than elsewhere (27% versus 57%, $F = 4.69_{1,30}$, $P = 0.038$), and lower scores on MDS4.3 ($F = 4.73_{1,30}$, $P = 0.038$).

The strongest relationship for the presence/absence of echidna visits was with the score on axis 2 of the ordination ($F = 8.92_{1,30}$, $P = 0.008$), which indicated that echidnas preferentially visited better-drained ground, and steeper (mean = 4.13° versus 2.02°) slopes ($F = 4.44_{1,30}$, $P = 0.044$). Shrub cover was less where echidnas visited than elsewhere (mean = 10 versus 29 %, $F = 5.31_{1,30}$, $P = 0.028$).

Relationships between species

Brushtail possum and Bennett's wallaby visits were positively correlated (r = 0.352, d.f. = 30, p = 0.048). The presence of cats was positively associated with visits of long-nosed potoroos ($F= 5.3_{1,30}$, $P = 0.028$) and southern brown bandicoots ($F= 29.3_{1,30}$, $P <0.001$), but negatively associated with macropod scat density ($F= 4.4_{1,30}$, $P = 0.045$). Both southern brown bandicoots and cats decrease rapidly in visits with distance from dense housing (Figure 2).

Discussion

Distance to housing

Distance to housing was prominent in the models for the long-nosed potoroo, the southern brown bandicoot and the cat, with all three species more active at stations closer to dense housing. For the southern brown bandicoot, this is consistent with previous studies that have shown that bandicoot diggings and activity are common in urban and exurban areas (Daniels and Kirkpatrick 2012; Bryant et al. 2017). The relationships between long-nosed potoroos and urban environments are not well-studied, although Daniels and Kirkpatrick (2012) reported them from some exurban environments. Not surprisingly, cats were associated strongly with dense housing; the surprise was its positive associations with long-nosed potoroos and southern brown bandicoots. Both native mammals were present more widely than the range of the cat in the reserve, but the numbers of visits per site were higher within the range of the cat than otherwise. Given that the direct effects of the cat on such mammals is almost certain to be negative, through the disease toxoplasmosis and direct predation, the alternative explanations for the association between these species are: 1) that the habitat for these mammals in the reserve is better close to dense housing than elsewhere and the cats are domestic, fed by the householders; 2) that the habitat is better near the housing and the cats are attracted by the high density of prey; 3) that the small mammals have elevated populations close to dense housing because they utilise domestic gardens as well as the ecosystems in the reserve, as do the domestic cats. The first two hypotheses are not consistent with the strong effect of proximity to dense housing in the same multiple regression models as other environmental variables. This variable, thus, has an effect independent of the other variables included in the models, and is more explanatory than them. The third hypothesis is consistent with observations of bandicoots occurring in exurban gardens (Daniels and Kirkpatrick 2012) and with the high productivity associated with the elevated fertility and moisture availability of suburban gardens (Falk 1976; Bidwell et al. 2006; Bell et al. 2011).

Brushtail possums are well-known inhabitants of urban environments in Australia (Kerle and How 2008); however, we found no evidence of increased activity of this species closer to housing.

The negative relationship between macropod scats and cat presence may be the result of the concentration of graminoid-rich vegetation away from dense housing.

While dogs on leads are permitted on major walking tracks within the reserve, we did detect them on camera off-lead within the bush matrix. However, the number of such dog detections were too few to determine their relationship with housing and native mammal activity. Bryant et al. (2017) found quenda diggings were negatively correlated with access to reserves by domestic dogs.

The resources created by gardeners may have a fecundity and survival effect that outweighs mortality from high numbers of domesticated mesopredators and also provide a complex environment within which predation may be less effective. Thus, high mesopredator abundances and high mammal abundances are independently determined by the actions of householders in maintaining domestic animals and creating and maintaining gardens rich in food resources for native animals. The models suggest that elevated populations of mammals may also partially depend on dense sheltering growth in the native vegetation near the gardens, indicating the desirability, for conservation of native mammals, of a low fire frequency (15–25-year intervals). Mosaic burning is desirable as several native species appear to benefit from recent burning.

Fire

Fire regimes can be an important influence on mammal community assemblages in Australian ecosystems. For protected areas adjacent to urban areas, fire management is a critical issue for land managers because of the risk of bushfire to human life and property. Within our study reserve, fire is primarily used as a tool to manage this risk. Time since last fire featured in the models associated with southern brown bandicoot and Bennett's wallaby activity (visits, diggings and scats). The negative effect of recent fire on total diggings is consistent with that found for mainland southern brown bandicoots (Claridge and Barry 2000) and may reflect a lack of shelter and food resources. However, other studies have found limited effect on their activity following fire (Shan et al. 2006; Hope 2012). The presence of cats at our study site may have played a role in our study as Arthur et al. (2012) suggested that cat predation may retard southern brown bandicoot recovery after fire. The positive association of southern brown bandicoots with areas of the reserve that had been burnt several times suggests that burning may be a positive influence for this species over the longer term; but this requires further investigation. In contrast to southern brown bandicoots, Bennett's wallaby activity (visits and macropod scats) was greater in recently burnt areas of the reserve, most likely reflecting a tendency of these macropods to feed on fresh growth in recently burnt areas (Kirkpatrick et al. 2011; Styger et al. 2011; Kirkpatrick et al. 2016).

While fire regime variables were in the models for total diggings, macropod scats, Bennett's wallaby visits and southern brown bandicoot visits, the effects of fire regime on vegetation structure is also likely to be important for those species with shrub cover or vegetation density in their models (Monamy and Fox 2000). The pademelon and potoroo fit this description. The opposite responses to time since fire of Bennett's wallaby and brushtail possums is striking. Such differences between species in response to fire regime and vegetation have been widely observed in non-urban areas (Catling et al. 2001; Lindenmayer et al. 2008; Arthur et al. 2012).

Brushtail possum visits were positively associated with recent fire (axis 4); this is consistent with an increase in activity following cool burns in dry forest (Driessen et al. 1991) and wildlife in forest and woodland habitats (Lindenmayer et al. 2008) but not with abundance after wildfire in the study by Catling et al. (2001).

Other environmental factors

The positive relationships between numbers of diggings and two of the more abundant digging species gave confidence in their representation of this group of animals. The three most abundant excavators in the area, the long-nosed potoroo, the southern brown bandicoot and the echidna, consume invertebrates and fungi. The increase in diggings with increase in tree basal area was an expected consequence of the association of fungi with tree root systems (Johnson 1994). The positive effect of *Eucalyptus amygdalina* basal area in the model for the southern brown bandicoot is consistent with the year-round importance of fungi in their diet (Quin 1985; Mallick et al. 1998) and the importance of trees in supporting soil fungi (McMullan-Fisher et al. 2010). However, no such relationship was recorded for fungivorus long-nosed potoroos, which occurred widely throughout the reserve. The association of the long-nosed potoroo with high shrub cover and good soil drainage in its best model is consistent with previous descriptions of its habitat (Seebeck et al. 1989; Bennett 1993; Norton et al. 2010), although at the local scale Bennett (1993) also found that the long-nosed potoroo was not strongly correlated with any structural feature of the vegetation. The echidna appears to be as strongly associated with well-drained ground as the other two species but was less often observed where shrub cover was high than where it was low. The negative effect of vegetation density 50–100 cm above the ground with total diggings may be associated with the lower density of diggings on gentler slopes also indicated by the best model. Dense stands of *Melaleuca* were often found on flat ground.

It was not surprising that possum scats increased as total basal area increased, given the importance of trees for both eastern ringtail and brushtail possums. Brushtail possums feed on the ground to some extent (Kerle 1984; MacLennan 1984), explaining the negative association with fern cover in their best model and their positive association with macropod scats.

The positive relationship of macropod scat counts and Bennett's wallaby activity gives some confidence that the one-off count has some meaning. However, the absence of a relationship with rufous-bellied pademelon visits is puzzling, especially as their visits were much more frequent than those of wallabies. The model for macropod scats may reflect the importance of graminoids as a food source for macropods in the area, a preference for open vegetation for feeding (McArthur et al. 2000) including recently burned areas as previously mentioned. However, both the model for the Bennett's wallaby and that for the rufous-bellied pademelon included a positive influence of vegetation density 50-100 cm above the ground, seemingly contradicting the preference for openness implied by the macropod scat model. However, this relationship reflects the well-known tendency of both wallabies and pademelons to shelter in dense vegetation during daylight hours (Le Mar and McArthur 2005; While and McArthur 2005). The avoidance of dense fern cover indicated by the wallaby model could reflect the association of *Pteridium esculentum* with low graminoid cover.

The inverse relationship between macropod scat counts and digging density indicates a topographic segregation of sets of species, with the graminoids eaten preferentially by the macropods being most abundant on the gentler slopes, while the resources favoured by the digging animals are most abundant on well-drained ground.

Conclusions

While the reserve supports many mammal species, some of which appear to benefit from the adjacent suburbia, there are several species that may have been disadvantaged by the encroachment of suburbia, its associated disturbances and the increasing isolation of the reserve. Eastern quolls (*Dasyurus viverrinus*), eastern bettongs (*Bettongia gaimardi*) and the platypus (*Ornithorhynchus anatinus*) have been recorded from the area (Driessen and Jarman 2010; Driessen and Jarman 2014) but no platypus have been recorded in the reserve in over a decade of surveys and bettongs have only occasionally been recorded and the eastern quoll once (Driessen et al. in press; Driessen and Jarman unpublished data). During the past three years of survey, the Tasmanian devil (*Sarcophilus harrisii*) has been recorded for the first time (Driessen et al. in press). The reserve on its own is too small to support a devil population, suggesting a wider use of the surrounding developed areas. The reserve has habitat that could support the bare-nosed wombat (*Vombatus ursinus*), but the species is absent.

We conclude that the effects of suburbia on native mammals currently occurring on adjacent reserved land are positive or neutral, depending on taxon, in the context of the recent fire regimes. The reserve is isolated from other areas of native vegetation by suburbia and farmland, so could theoretically be subject to relaxation. However, we suspect that the urban matrix may be permeable to most native mammals in Hobart in the same way as it is permeable to lizards (Jellinek et al. 2004).

Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

Ethics approval

This study followed the Standard Operating Procedures for Camera-trapping of Wild Tasmanian Mammals 2013 by the Department of Primary Industries, Parks, Water and Environment.

Consent to participate

Not applicable.

Consent for publication

Consent for publication was obtained from the Tasmanian Government. All authors consent for the publication.

Availability of data and material

Data and material are available from the authors upon written request.

Code availability

Not applicable

Author's contributions

Jamie Kirkpatrick designed the vegetation, diggings and scat data collection, collected the vegetation data and undertook most of the analysis and writing up.

Michael Driessen was the major designer of the larger project, collected much of the mammal and environmental data and contributed substantially to the writing of the paper.

Peter Jarman contributed to the design of the project, collected much of the mammal data and contributed to the writing of the paper.

Lauren Jakob collected the diggings and scat data and contributed to the writing of the paper.

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Tables

Table 1 Variables used in analyses

Factor	Description
Bare ground	Bare ground and moss cover not overshadowed by any vegetation < 1 m tall (%)
Bennett’s wallaby	Number of *Notamacropus rufogriseus* visits per site 2018
Brushtail possum	Number of *Trichosurus vulpecula* visits per site 2018
Cat	Presence or absence of *Felis catus* at a site during 2018
Density (50–100 cm)	Cover on density board 50-100 cm above the ground, March 2018
Density (0–50cm)	Cover on density board 0-50 cm above ground, March 2018
DIST	Distance (m) of quadrat from nearest house on any lot size
DISTD	Distance (m) of quadrat from nearest high-density housing (250–1000 houses/km^2)
Echidna	Presence or absence of *Tachyglossus aculeatus* at a site during 2018
Euca amBW	Basal area of *Eucalyptus amygdalina* (m^2 per ha)
Fern cover	Outline cover of *Pteridium esculentum* 2018
Gram cove	Outline cover of monocotyledonous plants 2018
Long-nosed potoroo	Number of *Potorous tridactylus* visits per site 2018
Macropod scat	Number of scats of Macropodae in 10 x 10 m quadrat
MDS AXIS 4 1	Score on first axis of the ordination
MDS AXIS 4 2	Score on second axis of the ordination
MDS AXIS 4 3	Score on third axis of the ordination
MDS AXIS 4 4	Score on fourth axis of the ordination
NoOfFires	Number of fires between 1988 and 2018
Possum scats	Number of scats of possums (*Trichosurus vulpecula* and *Pseudocheirus peregrinus*) in 10 x 10 m quadrat
Shr cove	Outline cover of shrubs < 1 m tall (%)
Slope	Slope of quadrat in degrees
Southern brown bandicoot	Number of *Isoodon obesulus* visits per site 2018
Spec rich	The number of species of vascular plant in a 10 x 10 m quadrat

Rufous-bellied pademelon	Number of *Thylogale billardierii* visits per site 2018
Total diggings	The number of excavations and associated mounds of native animals in a 10 x 10 m quadrat
TotBW	Basal area of trees (m^2 per ha)
YearsSinceLastFire	Number of years since last fire in 2018.

Table 2 Mean scores on ordination axes of plant species occurring in 80 10 by 10 m quadrats. *** P < 0.001, ** P < 0.01, * P < 0.05 (One-way ANOVA of scores against presence/absence of species). s = shrub, c = climber/scrambler, g = monocotyledonous plant, h = herb.

Species	MDS4.1	MDS4.2	MDS4.3	MDS4.4
Allocasuarina monilifera s	-0.1302***	0.0303	-0.0502*	0.0811***
Amperea xiphoclada s	-0.2270***	0.1072	-0.1053	-0.1236*
Aotus ericoides s	-0.0676***	0.0645***	0.0081	0.0299*
Baeckea ramosissima s	-0.1942***	0.2292	-0.0036	0.0230
Banksia marginata s	-0.2522**	-0.0565	0.2470	-0.0222
Bossiaea cinerea s	-0.2834***	-0.0710	-0.0730*	0.0278
Cassytha glabella c	-0.2239**	0.0275	-0.0144	-0.0034
Cassytha pubescens c	0.0186	0.1148	-0.0507	0.1665***
Dillwynia glaberrima s	-0.1747**	0.1230*	0.1205**	0.0603
Empodisma minus g	0.0928	0.2857***	-0.0576	0.0630
Epacris impressa s	-0.0962***	0.0438	0.0273	-0.0487**
Gahnia radula g	-0.2854**	-0.3018***	0.1412*	0.1684**
Gonocarpus tetragynus h	-0.2827***	-0.0494	-0.0513	-0.0555
Gymnoschoenus sphaeroc. g	0.1726*	0.3758***	0.0389	0.0826
Hibbertia acicularis s	-0.1973**	-0.0125	0.1042*	0.0127
Hypolaena fastigiata g	-0.2420***	-0.0943*	0.1126**	0.0565
Lepidosperma filiforme g	-0.2182**	-0.0319	0.0923	-0.0726
Leptocarpus tenax g	0.0233	0.0945***	0.0064	0.0116
Leptospermum scoparium s	-0.0658***	0.0142	-0.0027	0.0275*
Leucopogon collinus s	-0.1733***	0.0225	0.0509	-0.0644*
Leucopogon ericoides s	-0.0783	0.0008	-0.0559	0.0326
Melaleuca squarrosa s	0.1313	0.3303***	0.0635	-0.1331**
Pimelea linifolia s	-0.0230	0.0303	-0.0463*	-0.1238***
Restio monocephalus g	0.1070**	0.1626***	0.0452	0.0443
Schoenus lepidosperma g	-0.1090*	0.1116*	-0.0845*	-0.0793*
Stylidium graminifolium h	-0.1759**	0,1630**	0.0460	-0.1437***
Styphelia adscendens s	-0.2599**	-0.0659	0.1801**	-0.1745**

Table 3 Pearson product moment correlations of environmental and vegetation variables with scores on the four ordination axes. *** P < 0.001, ** P < 0.01, * P < 0.05.

Variable	MDS4.1	MDS4.2	MDS4.3	MDS4.4
Eucalyptus amygdalina basal area	-0.133	0.100	0.077	0.129
Total basal area	-0.072	0.187	0.095	0.085
Shrub cover	**-0.306****	**0.379****	0.172	0.000
Fern cover	**0.225***	**-0.222***	-0.010	-0.162
Graminoid cover	0.141	**0.457*****	**0.346****	**0.328****
Bare ground	**0.299****	0.081	-0.153	**-0.222***
Species richness	**-0.810*****	**0.232***	0.183	-0.023
Density (0–50 cm)	**0.378****	**0.305****	0.146	-0.021
Density (50–100 cm)	**0.497*****	0.077	0.184	0.145
Years since last fire	0.044	-0.258*	0.037	**0.675*****
Number of fires	-0.128	0.218	-0.154	**-0.594*****
Distance to nearest house	0.158	0.094	**0.387*****	0.047
Distance to nearest dense houses	0.086	-0.149	**0.379****	**0.361****
Slope	**0.285***	**-0.409*****	0.033	0.157

Figures

Figure 1

The locations of transects and houses in the study area

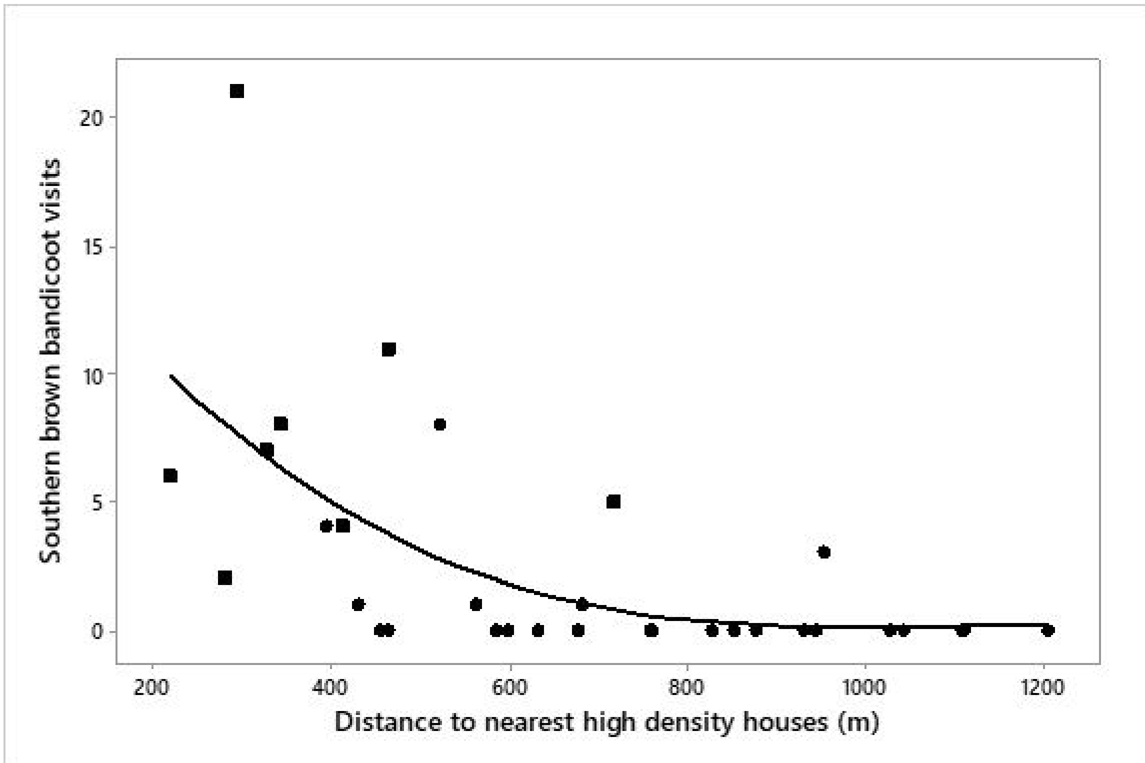

Figure 2

Relationship between southern brown bandicoot visits and distance to the nearest high-density houses, showing sites with cat observations (squares)