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Environmental factors influencing the distribution of the Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni*)

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Abstract. Determining the factors that drive the distributions of threatened species is often critical for informing effective conservation management actions. Species distribution models can be used to distinguish common habitat features shared by limited historical records and identify other areas where a species might persist. In this study, we built a species distribution model for the Endangered and cryptic Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni*). We fitted generalised linear models using incidental records and presence-absence data from surveys between 1969 and 2018. In the models we included the variables rainfall, percentage native vegetation in the surrounding 2 km^2, and post-fire vegetation age. The modelling suggested that rainfall and to a lesser extent post-fire vegetation age are good predictors of dunnart occurrence, with dunnart occurrence greatest in areas of high rainfall ($>$600 mm) and vegetation age classes $<$30 years post fire. Potentially suitable habitat for the KI dunnart was predicted to be on the central-western side of Kangaroo Island. These results suggest that careful fire management could benefit the dunnart, and that decreased rainfall (as projected by Australian climate models), will be a threat in the long term. Extensive recent fires on western Kangaroo Island suggest that climate-related threats are already being realised.

Keywords: dunnart, fire management, Kangaroo Island, native vegetation, rainfall, *Sminthopsis fuliginosus aitkeni*, species distribution modelling, threatened species.

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Introduction

Understanding the factors that drive species distributions can underpin our perception of a species' biology, and inform the actions needed for species conservation (Jorgensen 2004). Species distribution models look for commonalities in environmental or spatial characteristics of sites where a species has been previously recorded, and identify other areas with similar characteristics that may also be suitable (Elith *et al.* 2011). These models can be particularly useful for threatened species that are cryptic or hard to detect due to their persistence at low densities and/or their elusive habits (Norris 2004; Joseph *et al.* 2006). For such species, these models can fill in knowledge gaps regarding both the species' range and habitat preferences and provide valuable information for conservation and land managers (Joseph *et al.* 2006).

In Australia there are 19 species in the marsupial genus *Sminthopsis* (family Dasyuridae), commonly known as dunnarts; eight are found mainly in arid areas, three in the semi-arid zone, four in the wet and monsoon tropics and seven in temperate parts of Australia (Peel *et al.* 2007; Van Dyck and Strahan 2008). Habitat preferences of *Sminthopsis* species native to temperate Australia are under-represented in ecological studies (Friend *et al.* 1997), and in particular associations with post-fire vegetation age remain poorly understood. *Sminthopsis murina*, *S. f. fuliginosus* and *S. dolichura* have been classified as early-to-mid successional species as their abundance peaked 2–6 years post fire in eucalypt woodland (Fox and McKay 1981; Fox 1982; Bamford 1986; Friend 1993). In contrast, *S. leucopus* was found to occur at a high percentage of sites 6–15 years post fire, suggesting preferences for mid-successional habitats (Wilson and Aberton 2006).

The Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni* (following the nomenclature of Jackson and Groves (2015)), hereafter referred to as the KI dunnart) is a range restricted and poorly understood taxon. This dunnart is carnivorous, has a small body mass (≤25 g), and is restricted to Kangaroo Island in South Australia. The taxonomy of the taxon is unresolved, and it has been previously named *Sminthopsis aitkeni* (Kitchener *et al.* 1984). It is listed nationally as Endangered (under the name *Sminthopsis aitkeni*) by the *Environment Protection and Biodiversity Conservation Act 1999*, largely due to its restricted range and the scarcity of records. Between 1969 (when it was first discovered) and 2018, individuals had been reported on 46 occasions at 21 sites (Jones *et al.* 2010; Gates 2001, 2011; Hohnen *et al.* 2019). All records since 1990 have come from the western half of the island, and the taxon has not been detected in the east (east of Parndana) since 1979. Of these 46 records, 41 are from public land and five from private land.

In terms of habitat characteristics, the KI dunnart has been found in woodland dominated by *Eucalyptus remota*, *E. baxteri* or *E diversifolia* and *E. cladocalyx* (Gates 2001). Predation from feral cats (*Felis catus*) and presence of the root rot disease *Phytophthora cinnamomi* may also influence the local persistence of KI dunnarts (Gates 2001, 2011). *Phytophtora cinnamomi*, common across Kangaroo Island, causes dieback in vulnerable plant species, such as grass trees *Xanthorrhoea australis*; the grassy skirts of this species are known to be key shelter sites for the KI dunnart (Gates 2001). Low detection rates in individual surveys have limited previous analyses of fine or broad scale habitat preferences (Gates 2001; Hohnen *et al.* 2019).

In this study we examined the habitat associations and potential distribution of the Kangaroo Island dunnart using species distribution modelling. Spatial information for the variables rainfall, time since fire, and native vegetation, exists for Kangaroo Island, and these variables were included in our models. Unfortunately, no spatial layers describing variation in feral cat density or *P. cinnamomi* infestation across Kangaroo Island exist, so these factors could not be included. Overall, the aim of the study was to (i) better understand the environmental correlates of KI dunnart records and (ii) identify previously unsurveyed areas that have habitat characteristics potentially favourable to KI dunnarts. This information could be used by land managers to direct ongoing surveys and monitoring, and to guide conservation and management efforts to support persistence of the dunnart in the long term. Bushfires in early 2020 burned much of the vegetation in the western Kangaroo Island, providing some urgency to improving our understanding of the dunnart's environmental requirements.

Materials and methods

Location

Kangaroo Island (4405 km^2) is located off the South Australian coast 126 km from the city of Adelaide. The island typically receives between 440 and 820 mm of rainfall per annum, with most rain falling on the western side and in the winter months (June–August). The western half of the island is generally higher elevation than the east (Bureau of Meteorology 2020), but the highest point on the island is Mt McDonnell (299 m), on the north coast. Remnant native vegetation covers approximately 42% of the island. The dominant overstorey species include *Eucalyptus diversifolia*, *E. remota*, *E. baxteri* and *E. cosmophylla*, as well as stands of the taller *E. cladocalyx* in some areas (Ball and Carruthers 1998).

Detection/non-detection data

KI dunnart detection/non-detection data were collated from surveys and incidental records between 1969 (when the taxon was first recorded) and 2018 (Fig. 1). There were 46 records of the KI dunnart (46 total), nine of which were incidental (Supplementary material Table S1). Incidental records were collected through discussion with The Kangaroo Island Natural Resource Management Board and from South Australian Museum records, and from previous studies such as Gates (2001). The detection methods used in most surveys consisted of pitfall, Elliott and camera traps (Herbert 1996; Robinson and Armstrong 1999; Gates 2001; Jones *et al.* 2010; Molsher *et al.* 2017; Hodgens and Groffen 2018; Hohnen *et al.* 2019). The number of traps per site and the number of nights surveyed varied considerably between surveys (see Supplementary material Table S1 for more details). For sites where there were multiple surveys the earliest survey of that site was included and the others omitted, to avoid pseudoreplication (15 data points).

GIS data

In the models we initially included the variables: elevation (m) (Geosciences Australia 2017), average annual rainfall (mm) from 1975 to 2005 (referred to as rainfall) (Bureau of Meteorology 2020), percentage native vegetation within 2 km^2 of a given 100 × 100 m cell (South Australian Department of Environment and Water, unpubl. data), and post-fire vegetation age in years (referred to as time since fire) (South Australian Department of Environment and Water, unpubl. data). Elevation and rainfall were represented by raster layers with a cell size of 30 m and 100 m, respectively. Post-fire vegetation age was calculated from the Kangaroo Island fire history layer which details annual fire extent between 1931 and 2018 (South Australian Department of Environment and Water, unpubl. data). The layer has a resolution of 0.01 m and is the product of three types of data with varying spatial accuracy, (i) georeferenced aerial photos and satellite imagery including Landsat, SPOT, and Modis series, (ii) GPS tracks from helicopters or planes flying around fire scars, and (iii) hand drawn maps on paper that estimate fire scar boundaries. The layer is updated at least twice yearly and also on an *ad hoc* basis such as after a major wildfire incident. Fire history information was not known for three records (i.e. a fire may have occurred prior to 1931), and these sites were unfortunately excluded from the analysis. Percentage overstorey vegetation was calculated using a Kangaroo Island native vegetation layer (Ball and Carruthers 1998). This layer was originally produced in 1998 and has a spatial accuracy of 0–25 m, and a resolution of 0.01 m. The survey

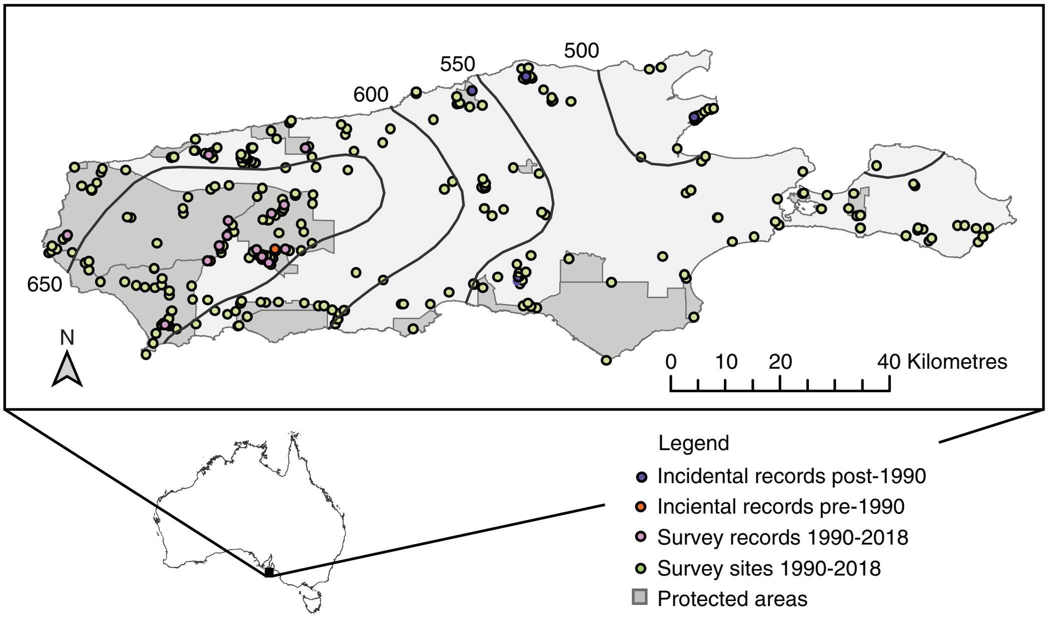

Fig. 1. All Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni*) detection and non-detection locations and incidental records between 1969 and 2018, and also showing protected areas and average annual rainfall isohyets.

dataset includes some records from prior to the production of the vegetation spatial layer; however, we expected little temporal variation as most KI dunnart records are from conservation land that would have remained little changed over time. To calculate the percentage overstorey vegetation in the surrounding 2 km^2, we used the shapefile to produce a raster layer with a cell size of 100 m, where each cell with native vegetation was coded as 1 and without was coded as 0. Then the final raster layer was produced by taking the average of cells in a 2 km^2 area surrounding the original cell. We chose this size as we were interested in understanding if dunnart occurrence was higher in areas of more continuous bushland habitat rather than on bushland edges. Also, at smaller spatial scales (for example, 400 m^2) there was little variation in the amount of bushland surrounding survey sites. More information regarding variation in the raw data set of the variables time since fire, native vegetation cover and rainfall is available in Fig. S1.

Analysis

Variation in the location of detection/non-detection records of KI dunnarts at survey sites with differing environmental variables was examined using generalised linear models, in the program R (R Core Team 2018). Correlation between the variables was first assessed in a univariate analysis using Spearman's rank correlations. Elevation was highly correlated with rainfall ($r_s = 0.83$) and as a result the variable elevation was omitted from the analysis. Correlations between all other variables were less than 0.1 and were therefore included in the analysis. All combinations of the remaining three variables were included and analysed in a generalised linear model selection framework. Model fit was examined using Akaike Information Criterion (AIC) values following the approach outlined in Burnham and Anderson (2002). If competing models were within two delta AIC points of the top model, a model averaging approach was taken using the R package 'MuMin' (Bartoń 2013). This approach uses all models in the model set (that include all combinations of all variables) to produce 'average' coefficient estimates and model predictions. The calculations are weighted such that the models that fit best contribute most to the estimates, and models that fit worst contribute the least. From the model averaged output, we mapped potentially suitable habitat for the KI dunnart using the packages 'raster' and 'rgdal' (Hijmans and van Etten 2012; Bivand *et al.* 2020). These packages use the raster layers (rainfall, time since fire and percentage native vegetation within 2 km^2) and the model averaged coefficient estimates that weight the importance of each of these variables, to predict suitable habitat across the island.

Results

Our models are based on 17 detection sites and 178 non-detection sites. The sites occupied by the dunnart were between 2 and 65 years post fire (on average 24 years post fire), received between 626 and 803 mm of rain annually (on average 677 mm) and had between 46 and 100% native vegetation cover in the surrounding 2 km^2 (75% on average). The species distribution modelling suggested that two variables were related to dunnart occurrence: rainfall and to a lesser extent, time since fire. The variable rainfall was included in all well-supported models (ΔAIC ≤ 2; Table 1). The 95% confidence intervals of the model averaged coefficient estimates did not overlap zero for the variable rainfall, but did for the other two variables, time since fire and native vegetation cover (Fig. 2). The variable time since fire was included in the top two best fitting models (Table 1). Relative variable importance values were highest for rainfall, time since fire and lowest for native vegetation cover (0.98, 0.75 and 0.39 respectively).

Table 1. Model ranking of variables describing Kangaroo Island dunnart occurrence across Kangaroo Island

Model	d.f.	AIC	ΔAIC	Model weight
Rainfall + fire	3	108.17	0.00	0.44
Rainfall + fire + vegetation cover	4	109.01	0.84	0.29
Rainfall	2	110.25	2.08	0.16
Rainfall + vegetation cover	3	111.41	3.24	0.09
Fire	2	116.1	7.93	0.01
Null	1	117.43	9.26	0
Fire + vegetation cover	3	117.44	9.27	0
Vegetation cover	2	118.92	10.75	0

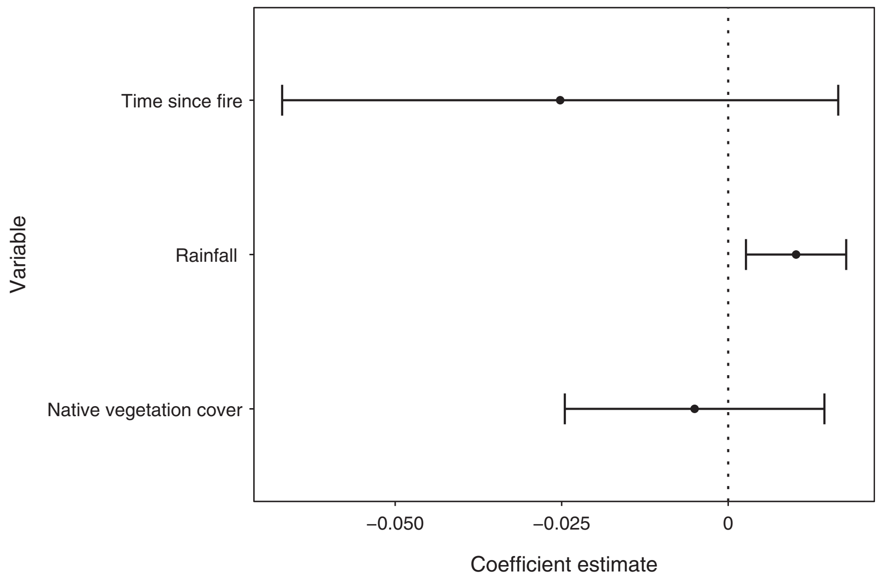

Fig. 2. Model averaged coefficient estimates with 95% confidence intervals of the variables time since fire, rainfall and native vegetation cover, describing potentially suitable habitat for the KI dunnart (*Sminthopsis fuliginosus aitkeni*). The term AIC refers to Akaike Information Criterion, and d.f. refers to degrees of freedom.

Model averaged predictions suggest that habitat suitability was highest at sites receiving high rainfall with vegetation in early and mid-successional stages <30 years post fire (Fig. 3). Model averaged output predicted that suitable areas for the dunnart are potentially in the central west and south west of the island (Fig. 4*a*). As time since fire is a variable likely to change annually as fires burn different parts of the island, the best fitting model that did not include the variable time since fire was also mapped (Fig. 4*b*). This model (that included just the variable rainfall) predicted that dunnart occurrence was also highest in the central west of the island.

Discussion

Habitat suitability for the KI dunnart appears to be strongly related to rainfall and was predicted to be highest in the central-west of the island, in areas that receive over 600 mm per annum. The KI dunnart may also occur more frequently in early and mid-successional vegetation that is <30 years post fire. Areas of habitat predicted by this study to be potentially suitable for the KI dunnart may also reflect the areas where the taxon can persist given habitat loss, and other threats that have emerged since European settlement (Scheele *et al.* 2017). Certainly, pre-1980 records from the central and eastern edge of the island suggest that the dunnart once occurred in a wider range of habitats, than it has been detected in more recently.

Rainfall is generally a strong predictor of mammal persistence and decline in Australia and elsewhere. Across Australia mammal declines correlate strongly and negatively with rainfall, as arid areas have lost most species and mesic areas the least (McKenzie *et al.* 2007; Start *et al.* 2012). For example, in the Kimberley region of Western Australia rates of small mammal decline vary along a rainfall gradient, with species such as the golden-backed tree-rat (*Mesembriomys macrurus*), scaly-tailed possum (*Wyulda squamicaudata*), and brush-tailed phascogale (*Phascogale tapoatafa*) disappearing from the more arid parts of their range and persisting only in the high-rainfall North Kimberley (Start *et al.* 2012). Rainfall may influence mammal populations by changing food availability, or the amount of vegetation cover available to provide shelter from predators (Start *et al.* 2012). The KI dunnart potentially may have declined

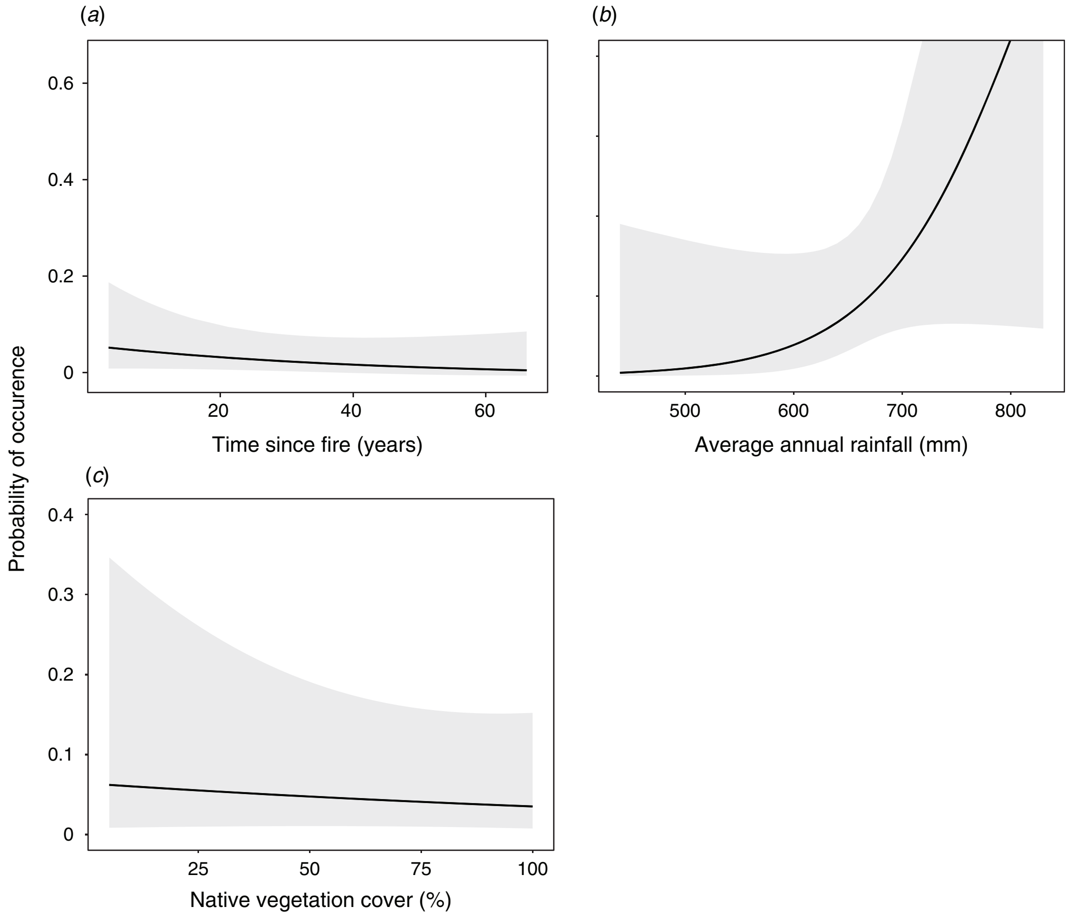

Fig. 3. Model averaged predictions of change in occurrence of the Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni*) with 95% confidence intervals of the variables (*a*) time since fire, (*b*) rainfall, and (*c*) native vegetation cover. The distribution of the raw data points can be seen in Supplementary Fig. S1.

in lower rainfall parts of the island such as the central and eastern regions, were they have not been detected in any recent (post 1990) survey.

Although rainfall varies from west to east across the island, so does the amount of native remnant bushland, which is much higher on western KI than in the east. Land clearing is likely to have contributed to the overall decline of the KI dunnart in the east. However, there are still large patches of remnant bushland in lower rainfall areas such Cape Gantheaume and in particular on the Dudley Peninsula (Fig. S2). These areas have been surveyed multiple times since 1990 but the dunnart was not detected. Perhaps while the dunnart can persist in drier areas (as there are historical records in the east), even before land clearing rates of site occupancy by the dunnart may have been higher in areas that receive more rainfall.

If rainfall is a key driver of KI dunnart habitat suitability, the impacts of climate change may become an increasing threat. Under all greenhouse gas emissions scenarios, winter rainfall in southern South Australia is projected to decrease by 15% by 2030, and by as much as 45% by 2060 (CSIRO Australia 2019). A reduction in mean annual rainfall recorded over the last five decades in south western Australia has been implicated in small mammal declines at long-term monitoring sites in that region (Wayne *et al.* 2017).

The percentage vegetation cover within 2 km^2 surrounding a site was not a good predictor of dunnart occurrence in this study. There was considerable variability in the amount of native vegetation surrounding most detection records. Sites with dunnart records on western KI were located both deep within the national park, and from near the border of the park and cleared land, potentially contributing to the lack of importance of this variable. Overall, this result suggests that other variables such as rainfall and post-fire vegetation age are better predictors of dunnart occurrence than percentage native vegetation cover within 2 km^2. Generally the KI dunnart has been found at sites with all of Kangaroo Island's dominant overstorey species associations including: *Eucalyptus baxteri*, *E. remota* and *E. diversifolia* (Gates 2001; Hohnen *et al.* 2019). Potentially, other vegetation characteristics such as density, structure, and availability of den sites are more important than the percentage of surrounding native vegetation. Unfortunately, this information wasn't collected as part of the field studies used in this analysis.

The results of the current analysis suggest that the KI dunnart preferred early-mid successional vegetation, though selection

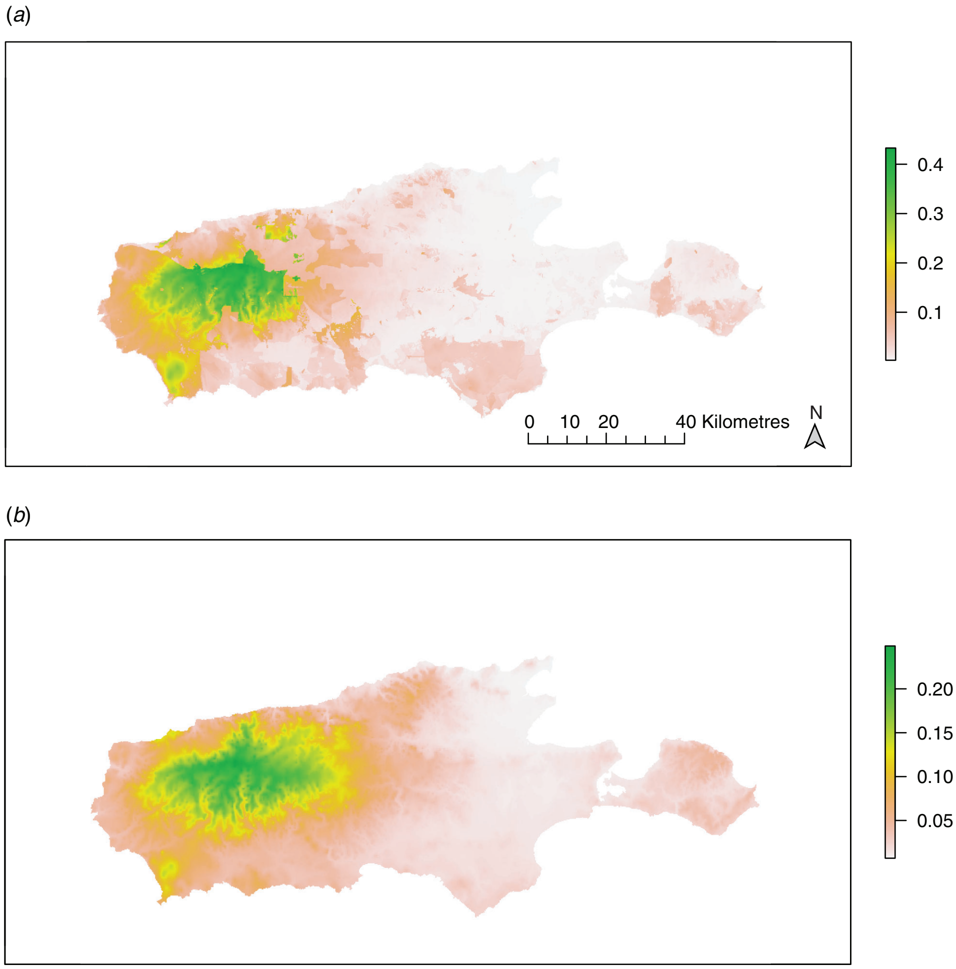

Fig. 4. Areas of potentially suitable habitat for the Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni*) based on (*a*) model averaged predictions from models that include the variables time since fire (calculated in 2018), rainfall, elevation and cover, and (*b*) the model that included the variable rainfall. This model was the best fitting model that included only static variables and did not include variables such as time since fire that may vary considerably year-to-year.

for this variable was not strong. Other dunnart species native to temperate Australia, such as *Sminthopsis murina*, *S. f. fuliginosus* and *S. dolichura* have been classified as early-to-mid successional species as their abundance peaked 2–6 years post fire in eucalypt woodland (Fox and McKay 1981; Fox 1982; Bamford 1986; Friend 1993). Although the KI dunnart appears to prefer vegetation age classes between 10–20 years post fire, further sampling in long unburnt habitats (20–40 years) and very recently burnt habitats (0–5 years post fire), which were sparsely represented in the dataset, would help clarify this pattern.

Fire management is currently a particularly important issue on the island as in January 2020 a catastrophic wildfire burnt almost half the island, including all known sites of dunnart occurrence since 1990. We acknowledge that preventing large scale wildfires is difficult, but some small-scale burns that occur in some areas every 15–30 years may increase the availability of vegetation <30 years post fire that the dunnart seems to prefer. Small scale burns that occur in Spring and Autumn, may also help increase vegetation age diversity, potentially reduce the vegetation fuel load in some areas, and favour the retention of small unburnt patches that could act as shelter for small mammals during the post-fire period. Feral cats have been found in other parts of Australia to target their hunting around recently burnt fire scars (McGregor *et al.* 2015*a*), and to have greater hunting success in areas where there is less vegetation (McGregor *et al.* 2015*b*). Therefore, retaining some unburnt vegetation within the fire scar may help small mammals persist in the early post-fire period. Fire management should also consider annual conditions such a drought (which may become more frequent as the climate warms) that influence the rate of post-fire vegetation regrowth.

One potential limitation of our study is that most records (all but four incidental records from the centre of the island) are from post 1990, after a large proportion of the central and eastern side of the island had been cleared. Potentially, further records would exist for that region of the island if less clearing had occurred, more subfossil studies had been done, or if surveys had occurred earlier and more extensively than they did. However, post-1990 surveys in bushland areas that remain in the centre of the island (including areas surrounding Parndana, Vivonne Bay, Kingscote, Cape Casini, and Lathami Conservation Park) and on the eastern side (including Dudley, Simpson and Lesueur Conservation Parks) have failed to detect the dunnart. Although existing pre-1990 records do suggest the dunnart may have persisted in a wide range of habitats, the dataset utilised here potentially more closely reflects suitable habitat (and occurrence) in the present day, at least in relation to habitat changes such as land clearing, and fire history. Another limitation is that few sites were trapped for sufficient nights to reach a 95% probability of dunnart detection (based on estimates of nightly detection probability outlined in Hohnen *et al.* (2019)). Extremely low nightly detection probability for the KI dunnart means there is a high likelihood of false absences. Methods that account for imperfect detection such as occupancy–detection modelling (Lahoz-Monfort *et al.* 2014; Guillera-Arroita 2017) were not possible in our analysis, as old survey data meant that detection histories could not be found for many of the survey sites.

Overall, KI dunnart habitat suitability appears be related to two variables considered in this study, rainfall and (to a lesser extent) post-fire vegetation age. Our models have identified key areas on western Kangaroo Island that may be suitable for the KI dunnart. As climate change is predicted to cause a decline in rainfall and perhaps foster conditions for more frequent fires in the coming decades, minimising atmospheric CO_2 concentration, is likely to be critical, albeit indirectly, to the dunnart's persistence in the future. Fire management practices that prevent such large-scale catastrophic fires as those seen in early 2020 and support the availability of early-mid successional vegetation stages may benefit the taxon. Future assessments of habitat use by the KI dunnart would benefit from the inclusion of fine scale habitat characteristics and the use of modelling techniques that account for imperfect detection. Monitoring in burnt and unburnt areas should also allow more insight into the taxon's preference for vegetation at different seral stages post fire.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgements

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