WWF

REPORT

AUS

2016

THIS REPORT WAS PRODUCED IN COLLABORATION WITH:

Department of Parks and Wildlife

Survival of Quokkas in the 2015 Northcliffe Bush Fire

Understanding the impact of intense and broadscale fire on an important population of quokkas in the southern forest of Western Australia

This document can be referenced as:
Bain, K., Halley, M., Barton, B., Wayne, A., McGilvray, A., Wilson, I., and Wayne, J. (2016). Survival of quokkas in the 2015 Northcliffe bush fire: understanding the impact of intense and broadscale fire on an important population of quokkas in the southern forest of Western Australia.

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Published in December 2016 by WWF-Australia.

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Acknowledgements:
This project was completed in partnership with the WA Department of Parks and Wildlife and was guided by a steering committee whose members provided advice during the project development, shared their expertise throughout the project and guided all stages of the project. Steering committee members included: Brad Barton (Regional Leader for Nature Conservation, Warren Region, Department of Parks and Wildlife), Dr Adrian Wayne (Research Scientist, Manjimup, Department of Parks and Wildlife), Alison McGilvray (District Leader for Nature Conservation, Frankland District, Department of Parks and Wildlife), Ian Wilson (District Leader for Nature Conservation, Donnelly District, Department of Parks and Wildlife), Julia Wayne (District Fauna Officer, Donnelly District, Department of Parks and Wildlife), Merril Halley (Species Conservation Manager for Southwest Australia, WWF Australia) and Dr Karlene Bain (Wildlife Ecologist, Python Ecological Services). In addition, Nic Slatter, Glenn Freeman, Alison McGilvray, Michael Sawyer and Julia Wayne from Department of Parks and Wildlife assisted the authors with field surveys.

CONTENT

1.	SUMMARY	3
2.	INTRODUCTION	6
2.1	Project scope	6
2.2	The quokka	6
2.3	The Northcliffe fire	7
2.4	Project objectives	9
3.	METHODS	10
3.1	The project area	10
3.2	Field survey for quokkas	11
3.3	Habitat assessment	12
3.4	Analysis	16
4.	RESULTS	18
4.1	Impact of the fire on known subpopulations	18
4.2	Current presence of quokkas within and surrounding the fire area	20
4.3	Factors driving occupancy	21
5.	DISCUSSION	24
5.1	Impact of the fire	24
5.2	Factors driving occupancy	24
5.3	Recolonisation	25
5.4	Management implications	25
5.5	Communication and integration of outcomes	27
6.	RECOMMENDATIONS	28
7.	REFERENCES	30

1. SUMMARY

The Northcliffe fire covered an area of' approximately 98,000 ha and burnt under intense conditions across much of this area, removing all vertical vegetation structure and leaving minimal unburnt refuge patches. The fire burnt at a scale that is considered large for this region and affected a significant proportion of critical habitat for the southern forest population of the quokka *(Setonix brachyurus)*, a threatened macropod endemic to southwest Australia. The southern forest supports the most extensive remaining quokka population on the mainland, and the most genetically diverse population of the species.

The purpose of this project was to determine the impact of the fire on existing subpopulations of quokkas occurring within the fire, to identify the effect of the fire on recolonisation patterns and to identify implications for the maintenance, or restoration, of a functional metapopulation.

A total of 126 sites were surveyed for quokkas within and surrounding the fire area. Field surveys were undertaken between February and June 2016. In addition, habitat attribute data were collected to improve our understanding of the factors driving occupancy and recolonisation patterns.

Fire impact

The fire resulted in the loss of 77% of known subpopulations of quokka within the fire-affected area. All quokka activity within the fire was found to be restricted to the edge of the fire or to a small number of internal sites, where low numbers of surviving quokkas were isolated from the edge in marginal or unsuitable habitat. All recorded faecal material for quokkas within the fire area was associated with small areas of unburnt canopy or was within 186 m of unburnt canopy, which indicates that movement patterns have been highly dependent on proximity to these refuge areas. This was also the case for quokkas occupying habitat on the edge of the fire. While their movements ranged up to 630 m into the burnt areas, all activity was tied into areas of unburnt canopy, where some vertical vegetation structure remained.

Overall, approximately 39 quokkas were estimated to be seeking refuge in isolated patches within the fire-affected area and 73 quokkas were estimated to be using burnt sites near the fire edge. It is estimated that approximately 500 individuals were lost from the fire-affected area, based on the number of known occupied sites and the average sub-population size for this area. Some of these animals may have survived by fleeing the fire into adjoining unburnt areas.

In some of the areas surrounding the fire, the density of quokkas was unusually high, with an estimate for one subpopulation of 11 quokkas/ ha. This may indicate that quokkas displaced by the fire have contributed to an additional degree of pressure on the carrying capacity of habitats outside of the fire.

Factors driving occupancy

Quokkas most commonly occupied post fire habitats in the Northcliffe fire area, where there was a complex vegetation structure (*3-7 layers of vegetation*), a sedge dominated understorey, low levels of feral pig damage to the soil and vegetation, and proximity to unburnt canopy. These findings can be linked to thermoregulatory requirements and predator avoidance behaviours that have previously been documented for this species.

Recolonisation

A large proportion of the fire-affected area was unoccupied at the time of this survey, with large distances (up to 36 km) separating occupied areas. The ability of quokkas to either disperse

through the burnt landscape or use refuge patches as 'stepping stones' is important in maintaining habitat connectivity and movement patterns at a landscape scale.

The internal refuge patches that are currently occupied by quokkas are in most cases smaller than 0.5 ha and surrounded by intensely burnt ecotypes. Quokkas surviving in these patches are highly vulnerable to factors such as predators and weather and may not survive to recolonise areas further afield. As the vegetation within the fire area recovers, the connectivity of suitable habitat patches will be critical to the ability of quokkas to move back into these areas unassisted. Additional disturbances that contribute to an increase in the distance between suitable habitat patches could contribute to these core areas remaining unoccupied. To avoid this, it is important that the internal areas of the fire are managed to ensure that habitat connectivity is re-established and maintained, to allow natural movement of quokkas back into the core of the area.

Given the scale and intensity of the Northcliffe fire area, four years would be expected to be the minimum period required for habitat to recover to a point where quokkas are able to move freely through the area.

Key recommendations for action include:

Project direction and context

- Clear project direction and focus.
  Develop a project plan that sets quantifiable objectives and ecological targets for quokka recovery within the Northcliffe fire-area, establishes priorities, establishes a clear monitoring, evaluation and reporting framework, identifies thresholds and triggers at which management action must be taken and provides a process for transfer of information and program improvement.

Communication and Partnerships

- Effective communication of the outcomes of this project and future directions to encourage integration of new knowledge into management, facilitate community engagement and interest, build professional collaborations, increase project capacity and to improve management effectiveness.

Threat mitigation and habitat management

- Manage further disturbance processes surrounding the fire that may compound the effects of the wildfire. For example, prescribed fire or harvesting activities applied within and to adjoining forest blocks within the next four years may increase the area of unsuitable habitat, increase habitat fragmentation and may even force animals displaced by the fire back into the fire affected area before the habitat is suitable, so increasing their vulnerability to predators, weather and other variables.

- Manage threatening processes in an integrated manner to increase survivorship of quokkas and allow animals to move out of the refuge patches as the surrounding habitat recovers. In particular, introduced predators, feral pigs, prescribed fire and harvesting activities should be the focus of active management for at least the next four years.

- Identify key riparian systems that are likely to be important for connecting refuge patches and facilitating movement patterns for recolonisation, both within and surrounding the fire-affected areas. Protect these riparian systems from further disturbance activities (e.g. fire, harvesting, feral pigs) that may reduce their suitability as movement corridors.

- In the event that unassisted recolonisation of core areas by quokkas has not occurred within six years, consider the need for assisted recolonisation, where suitable habitat is present.

Research/ Adaptive Management

- Improve management by addressing knowledge gaps. Key knowledge gaps that require focus include:

- Improve our understanding of recolonisation patterns by quokkas following large-scale fire events (population level). Specifically:
  - How long will the refuge patches continue to be important for quokkas as the surrounding areas recover?
  - How long does it take for quokkas to recolonise previously occupied sites at varying distances within the fire-affected area?
  - Are habitats within riparian systems more likely to be colonised before habitats outside of riparian systems? (Important for understanding the mechanisms of post-fire recolonisation and habitat protection priorities).
  - Are sites that were affected by lower intensity fire (canopy intact or scorch-level impacts) likely to be recolonised faster than sites that were affected by high intensity fire (defoliation)?
  - What are the other key factors driving occupancy and abundance patterns? (e.g. vegetation structure, distance from the fire edge, feral pig damage, sedge understorey)
- Improve our understanding of the factors limiting quokka recovery following a large-scale, homogenising fire (individual-level study that will inform population level management). Specifically:
  - How are quokkas within the fire area using habitat differently to those in unaffected areas (space use, habitat preference, movements)?
  - How are space use, habitat preferences and movement patterns related to refuge patch size, vegetation structure, food resources, water availability and feral pig damage?
  - Do quokkas exclusively use riparian systems to migrate between areas of suitable habitat?
  - What factors are driving mortality in the post-fire environment and how do these differ from what is happening in undisturbed habitat?
  - Do predators limit movement of quokkas out of refuge areas?
- Quantify the impact of introduced predators on the recruitment, demography and abundance of quokkas in a post-fire environment.
- Quantify the impact of feral pigs on vegetation structure and habitat quality
- Develop an understanding of the carrying capacity of habitat and how this is affected by an influx of individuals following a fire of this scale (e.g. impacts on habitat quality).
- Effects of large-scale, homogenising fire on sympatric species.

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2. INTRODUCTION

2.1 PROJECT SCOPE

Python Ecological Services was contracted by WWF-Australia, in February 2016, to undertake quokka surveys within and surrounding an area affected by the Northcliffe fire in 2015. The fire covered an area of approximately 98,000 ha and burnt under intense conditions across much of this area, removing vertical vegetation structure and leaving minimal (if any) unburnt refuge patches. The fire burnt at a scale considered large for a forested region and has affected a significant proportion of critical habitat for the southern forest population of the quokka *(Setonix brachyurus)*, a threatened macropod endemic to southwest Australia (Maxwell et al. 1996). This project addressed a need to determine the impact of the fire on existing subpopulations of quokka occurring within the fire, to identify the effect of the fire on quokka movement and recolonisation patterns and to identify implications for the maintenance, or restoration, of a functional metapopulation.

2.2 THE QUOKKA

The quokka is a medium-sized mammal with a geographic range that has dramatically declined since European settlement (Kitchener 1995, Hayward et al. 2003; Woinarski et al. 2014). This species is best known from Rottnest Island, where it is abundant but genetically depauperate (Sinclair 2001; Alacs et al. 2011). However, the species also occurs on the mainland of Western Australia where it was once common but is now classified as vulnerable under the Australian Environment Protection and Biodiversity Conservation Act 1999 and as ‘fauna that is rare or likely to become extinct’ under the State’s Wildlife Conservation Act 1950. Populations on the mainland include those in the northern jarrah forest between Perth and Collie, the Muddy Lakes area on the Swan Coastal Plain, the southern forest between Nannup and Denmark, and disjunct reserves north and east of Albany on the south coast (Sinclair 1998; de Tores et al. 2008; Sinclair and Hyder 2009; DEC 2013).

In the northern jarrah forest, the quokka requires dense riparian vegetation for diurnal refuge, the species utilises recently burnt vegetation for feeding, and fire is considered necessary to regenerate senescing habitat (Christensen and Kimber 1975; Hayward et al. 2005, 2007). In the southern forest, the quokka uses a diverse range of ecotypes outside of the riparian systems (Bain et al. 2015) and favours habitats with complex vegetation structure and low densities of woody debris (Bain et al. 2015).

The quokka has been lost from over 50% of its former range on the mainland of Western Australia since the time of European settlement (Woinarski et al. 2014). The southern forest now supports the most extensive remaining quokka population on the mainland, and the most genetically diverse population of the species (P. Spencer unpublished data). This is the population that has been affected by the Northcliffe fire and is the focus of this project.

Quokkas in the southern forest routinely move between 0.5 km and 10 km in a night within stable home ranges and have been recorded dispersing more than 14 km to establish new home ranges (Bain 2015), so movement across large distances is possible. However Bain et al. (2016) suggest that the quokka generally avoids movement through open habitat, possibly due to vulnerability to predation and thermoregulation requirements. They also suggest that large-scale and intense fires reduce the ability of quokkas to move between suitable habitat patches and may result in temporary habitat fragmentation.

The Northcliffe fire is likely to have resulted in significant habitat fragmentation for quokkas surviving within and surrounding the fire-affected area and it is important that recolonisation patterns are understood to enable effective management (or restoration) of the functional metapopulation in this area.

2.3 THE NORTHCLIFFE FIRE

In the summer of 2014/15, a large area of conservation estate burnt in southwest Australia, larger than in any season since 1960/61 (DFES 2015). A large proportion of this area was associated with the Northcliffe fire (approximately 98,000 ha) that burnt through large areas of national park and state forests, as well as through private lands.

Ignition of the fire occurred in the Shannon National Park, following a severe lightning storm that occurred on 28 January 2015. A deep trough off the west coast of Australia lingered for seven days, contributing to hot, dry, windy and unstable weather conditions.
This in conjunction with below average rainfall for the previous five years resulted in an elevated combustibility of the forest and intense fire behaviour (DFES 2015). Wind speeds reached up to 50 km per hour and flame heights of over 40 m were reported in the karri forests. The fire burnt under intense conditions for six days between 30 Jan 2015 and 4 February 2015, and continued burning under variable intensities until 12 February 2015 (Figure 1, page 8).

The fire had a significant impact on the flora and fauna of the area, with the vertical vegetation structure completely removed throughout most of the forest, the mid storey killed in most areas and some over storey tree species also killed outright. Australian flora and fauna are adapted to fire, and many species require fire for some aspects of their life history (e.g. Abbot and Burrows 2003). However, fire at this intensity and across this scale provides a number of challenges for species recolonisation. For fauna, one of these is being physically able to penetrate into the core of the fire area once these areas return to a state where they provide suitable habitat. The area directly impacted by the fire is up to 74 km long and 30 km wide.

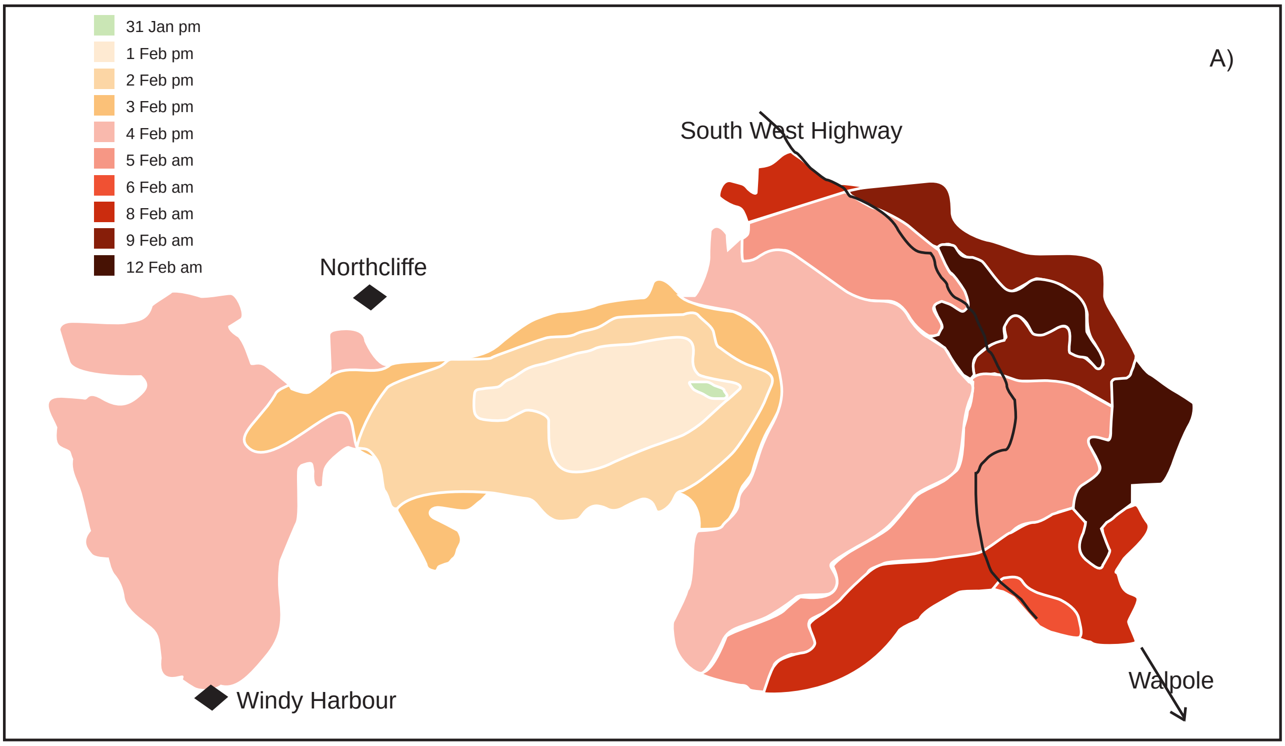

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Figure 1: Images of the Northcliffe fire. A) Fire development map between 30 January and 12 February 2015 (DFES 2015); B) Images of the smoke and flame heights generated by the fire; C) A landscape of homogenous fire outcomes: minimal unburnt pockets and complete vertical vegetation structure loss.

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2.4 PROJECT OBJECTIVES

Management of fire to protect taxa and ecosystems sensitive to fire regimes is of increasing importance in the context of climate change, given the expected increase in large-scale and intense wildfires and the increasing challenges associated with protecting mesic habitats and their ecological function (IPCC 2007; Williams et al. 2009). Current evidence indicates prescribed burning can create conditions conducive to the persistence and recolonisation of habitat by quokkas in the short-term; however large-scale and intense wildfires, such as the Northcliffe fire, can adversely affect quokkas in the short to medium-term and may well have long-term implications for habitat connectivity and metapopulation function (Bain et al. 2016). This is particularly the case where the scale of impact is such that animals can no longer safely move between suitable habitat patches. It is possible that the Northcliffe fire has occurred at such a spatial scale. The purpose of this project was to determine the impact of the fire on existing subpopulations of quokka occurring within the fire, to identify the effect of the fire on quokka movement and recolonisation patterns and to identify implications for the maintenance, or restoration, of a functional metapopulation.

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3. METHODS

3.1 THE PROJECT AREA

The southern forest occurs between Nannup and Denmark in southwest Australia. Compared to other areas of Australia, the southern forest has a relatively intact fauna, having experienced unusually low rates of mammal extinction in the past 200 years (McKenzie et al. 2007). The annual rainfall of this region (800 mm to 1400 mm) is uniquely high for Western Australia (Pink 2012).
The rainfall, dense vegetation, landscape productivity and the occurrence of moist and stable habitats have remained virtually unchanged for millions of years (Main and Main 1991, Hopper 1992, Wardell-Johnson and Coates 1996, Horwitz 1997, McKenzie et al. 2007).

The productivity and stability of habitats in the southern forest is of particular importance given predictions for a drying and warming climate in southwest Australia, which is expected to be associated with reduced vegetation health and an increase in disturbance regimes, such as fire, in many ecosystems (CSIRO 2001, Hughes 2003, IPCC 2007). These habitats support a diverse range of endemic, relictual and threatened species and offer a unique opportunity to conserve and protect a large number of species through landscape level management of threatening processes.

The Northcliffe fire occurred deep in the southern forest between Northcliffe and Walpole (Figures 1 and 2). The area contains a diverse range of ecosystems such as tall forests, woodlands, wetlands, creek systems, shrub lands, heath lands and granite outcrops. Forests in the region are dominated by jarrah *(Eucalyptus marginata)*, marri *(Corymbia calophylla)* and karri *(Eucalyptus diversicolor)*, with the karri growing up to 80 m tall. Ecotypes that are occupied by quokkas in this region often have a sedge-dominated understorey and a complex vegetation structure (Bain et al. 2015). About 83% of the area that burnt in the fire is National Park vested in the Conservation Commission for the purpose of conservation, much of which has been designated as such since the 1980s (DPaW 2016). An additional 13% of the area that burnt is State forest, also vested in the Conservation Commission but with a purpose of multiple use forest. The remaining area is private property.

This project focused on the areas of the Northcliffe fire that are vested in the Conservation Commission (both National Park and State forest) as well as a 1 km strip of conservation land adjacent to the fire-affected area (Figure 2).

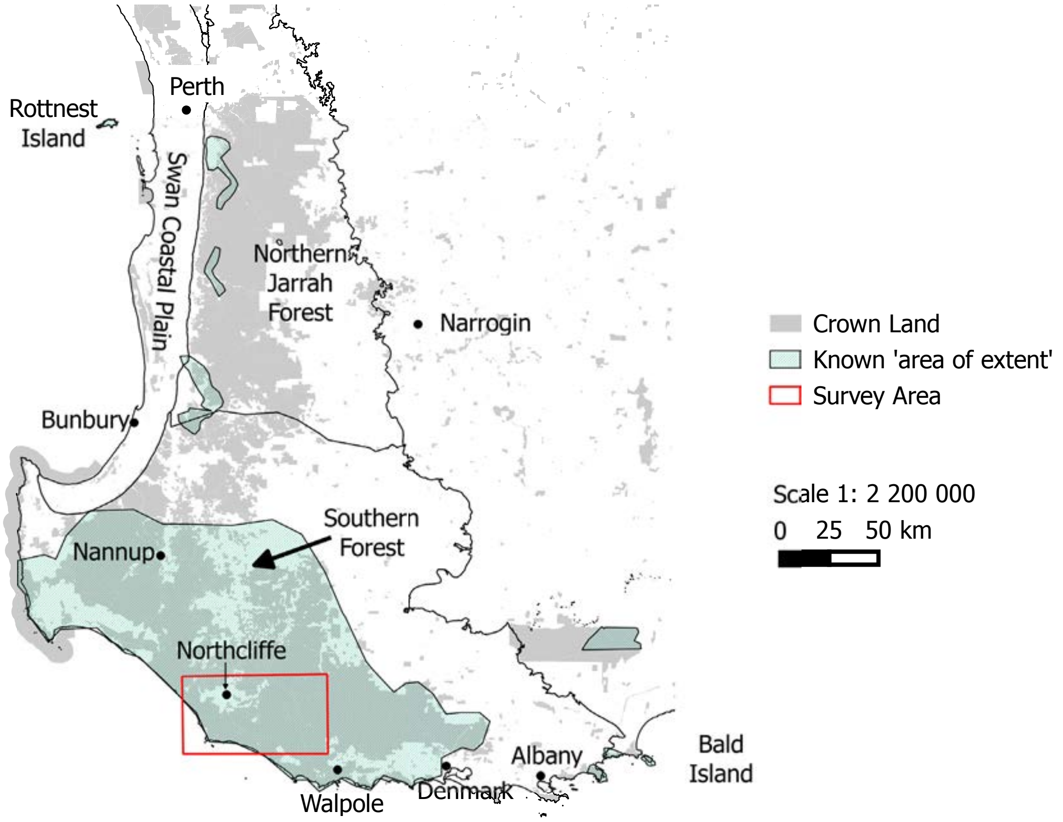

Figure 2: Location of the survey area and the known area of extent of quokkas in southwest Australia. Known extent has been determined from DPaW records of quokka sightings between 1990 and 2015.

3.2 FIELD SURVEY FOR QUOKKAS

A total of 127 sites were surveyed (approximate aggregated area of 504 ha). Site selection was based on:

1. Areas occupied by quokkas prior to the fire, which were identified using historical survey records and fauna sighting records provided by the Department of Parks and Wildlife. There were 28 of these sites, and they were selected to contribute to objective 1; i.e. to enable determination of the impact of the fire on known sub-populations of quokka within the fire. Areas known to be occupied by quokkas in the 5 years prior to the fire were used as the basis for selection of these sites.

Records with a high level of confidence were used where ever possible (i.e. sightings or confirmed presence of faecal material).
Where possible, sites were selected to maximise the likelihood of independence; i.e. greater than 5 km apart. However, this was not always possible without sacrificing large numbers of records.
Where sites were too close together to ensure independence, surveys were coordinated such that these sites were surveyed on the same day.
NB: using old charred scat as an indicator, 15 additional sites were found to have been occupied by quokkas prior to the fire during the surveys.

2. Areas on the edge of the fire, within the fire-affected area, that were likely to provide suitable habitat for quokkas prior to the fire, based on habitat attributes defined in Bain et al. 2015.
   There were 32 of these sites, and they were distributed in a range of fire intensities including canopy intact, canopy scorched and canopy defoliated. These sites were selected to contribute to objectives 2, 3 and 4. i.e. to document the current presence of quokkas within the fire; to document recolonisation patterns for quokkas within the fire area; and to improve our understanding of the factors driving recolonisation.

3. Unburnt areas adjacent to the fire-affected area that were likely to provide suitable habitat for quokkas prior to the fire, based on habitat attributes defined in Bain et al. 2015.
   There were 33 of these sites, and they were selected to contribute to objectives 2 and 3. i.e. to document the current presence of quokkas within and surrounding the fire; and to document recolonisation patterns for quokkas within the Northcliffe-fire area. These sites were deliberately selected to pair with transects on the edge of the fire, within the fire area, and were surveyed on the same day as their paired transect, as there was expected to be movement of animals between the two sites.

4. Areas greater than 1 km from the edge of the fire, within the fire, that were likely to provide suitable habitat for quokkas prior to the fire, based on habitat attributes defined in Bain et al. 2015. There were 34 of these sites and they were distributed in a range of fire intensities including canopy intact, canopy scorched and canopy defoliated. These sites were selected to contribute to objectives 2, 3 and 4. i.e. to document the current presence of quokkas within the fire; to document recolonisation patterns for quokkas within the fire area; and to improve our understanding of the factors driving recolonisation.

Quokkas in this region have a stable home range of up to 70 ha (maximum recorded diameter 3 km) and dispersal and emigration movements have only been recorded in early spring (August) (Bain 2015). For the purposes of this survey, it was assumed that large movements associated with dispersal and emigrations were unlikely to occur in summer/autumn. Survey transects were subsequently separated by at least 5 km to reduce the likelihood of more than one transect occurring within an animal's home range. Creek lines were targeted as a starting point for surveys, however the transect alignments traversed a range of topographical gradients, as quokkas in this region have been found to spend approximately 40% of their time in riparian vegetation and the remainder of their time in a range of other ecotypes (Bain et al. 2015).

Each site was surveyed for presence or absence of quokkas during a single summer-autumn period between February and June 2016. Presence was determined by walking a 2 km transect at each site and recording the occurrence of fresh faecal pellets within 2 m of the transect (Hayward et al. 2005b; Bain et al. 2014). All surveys were completed by trained observers to reduce potential errors in differentiating faecal pellets produced by quokkas from those of the western brush wallaby (Macropus irma) (Triggs 1996; Hayward et al. 2005b) and to minimize variation in detection probability arising from observer differences. The abundance of quokkas for each site surveyed was also calculated following Bain et al. 2015. These abundances were converted to densities by assuming each 2 km transect formed a linear strip 2 km long by 5 m wide.

3.3 HABITAT ASSESSMENT

A series of habitat attributes were recorded every 200 m along each transect.

These variables were selected based on current knowledge of habitat attributes that are likely to be important for quokkas in this region (Bain et al. 2015).

Attributes that were measured in the field included:

- Height of woody debris: within a 2 m radius of the survey point, the height of the elevated woody debris on the forest floor above the leaf litter was estimated (m). Woody debris consists of suspended leaves, twigs, branches and bark from the under storey, mid storey and over storey vegetation, but does not include the fine leaf litter.
- Density of woody debris: within a 2 m radius of the survey point the relative density of the woody debris was categorised as none (N), low (L), medium (M) or High (H) (Figure 3).
- Number of vegetation layers: looking upwards within a 2 m radius of the survey point, an estimate was made of the number of levels of vegetation including the under storey, multiple mid storey layers and over storey.
- Horizontal density of understorey: a photograph taken 0.5 m above and parallel to the ground, which is then analysed using digital cover estimation techniques in adobe photoshop (Macfarlane et al. 2000, Macfarlane et al. 2007).
- Percentage canopy cover: a photograph taken from chest height pointing directly upwards, with the camera held level.
  Average percentage of sky obscured by the crown foliage is then measured from the photograph using digital cover estimation techniques (Macfarlane et al. 2000, Macfarlane et al. 2007).
- Approximate area of feral pig damage (m2): feral pig damage was identified through distinctive digging and wallowing.
  For damaged areas, the approximate length and width of damage was estimated and recorded. For larger areas of damage, the damage was mapped in the field using a GPS and the area estimated from the arising polygon in QGIS software.
- Dominant vegetation type: The two dominant over storey, mid storey and under storey species within 5 m of the survey point were recorded and cross-referenced with vegetation maps (Mattiske and Havel 1998). Where the species recorded matched the vegetation type mapped, the Mattiske and Havel classification was used.
  Where there were discrepancies, the Mattiske and Havel descriptions were used to help classify the vegetation into an appropriate vegetation category.
- Faecal pellet age: Faecal pellet groups within 5 m of the survey point were counted and categorised into age groups including:
  Day old pellet groups, which have a glistening, light brown exterior and are moist and green when broken apart (Bain et al. 2015); faecal pellet groups that are slightly older but less than 1 week old, which have a darker brown-grey exterior but are often still soft and have some green material inside when broken apart; and older pellet groups, which have no green in the interior (Figure 4).

None: No visible woody debris

Low density: less than 20% of area is covered by woody debris

Medium density: 20-60% of area is covered by woody debris

High density: greater than 60% of area covered woody debris

Figure 3: Categorical assessment of the density of woody debris

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Fresh (less than one day old)

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Within one week old. Scats when broken apart still have soft green material inside.

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Older. When broken apart these are dry and brown or grey inside.

Figure 4: Examples of the three categories of faecal pellet groups: fresh, within one week and older.

3.4 ANALYSIS

Habitat models were developed to discriminate between locations where quokkas were present and those where they were absent. In order to reduce the number of variables to a level not likely to result in an over-fitted model, the procedure of Hosmer and Lemeshow (2000) was used, with a stricter cut-off of p>0.10 (Table 1).

These steps resulted in the removal of only one variable, understorey height, however a significant correlation was found between trash density and trash height (r2=0.83), and trash height was also removed from further analysis.

Table 1: Comparison of habitat variables at sites where quokkas were absent and present (burnt sites only)

Description	Mean (+/- SE)		t-test		Univariate Logistic Regression	
	Absent	Present	t	P	-2 Log likelihood	Sig.
Trash Height (TH)	0.17 (0.01)	0.098 (0.02)	2.51	0.01	-253.67	0.01
Veg Layers (VL)	1.89 (0.02)	3.52 (0.08)	-19.00	0.00	-136.63	0.00
Understorey height (UH)	1.05 (0.02)	1.07 (0.04)	-0.25	0.80	-257.42	0.80
Understorey density (UD)	56.77 (0.82)	68.33 (2.58)	-4.08	0.00	-248.63	0.00
Canopy cover (CC)	27.26 (0.88)	50 (2.63)	-7.56	0.00	-231.53	0.00
Pig Damage (PD)	3.50 (0.47)	0.373 (0.03)	2.00	0.04	-252.72	0.05
Distance to canopy (DC)	1548.67 (70.76)	12.53 (4.10)	6.57	0.00	-163.42	0.00
Distance to fire edge (DF)	2832.00 (102.22)	1439.14 (248.21)	4.02	0.00	-246.23	0.00
Distance to creek (DtC)	138.09 (10.36)	83.72 (12.78)	1.57	0.11	-255.15	0.09
Landform (LF)		Categorical			-250.85	0.01
Trash Density (TD)		Categorical			-252.94	0.01
Vegetation Type (VT)		Categorical			-254.73	0.02
Grass Present (Gr)		Categorical			-250.65	0.00
Sedge Dominant (SD)		Categorical			-224.21	0.00
Canopy Scorch (CS)		Categorical			-189.68	0.00

A backwards stepwise logistic regression (Stata10) with a probability of variable removal of 0.1 was then developed to select the subset of the remaining variables that best predicted the probability of occupancy (Table 2). Variables modelled included: the number of vegetation layers (VL), understorey density (UD), canopy cover (CC), distance to unburnt canopy (DC), distance to fire edge (DF), distance to creek (DtC), landform (LF), density of woody debris (DD), vegetation type (VT), sedges dominant in the understorey (SD), grass present in the ground cover (Gr) and the category of canopy scorch (CS). The importance of each variable within the model was determined by assessing the change in the log-likelihood ratio when that variable was removed from the model. The Hosmer and Lemeshow goodness-of-fit statistic (Hosmer and Lemeshow 2000) was used to assess the fit of the model at each step. In addition, the Akaike Information Criterion (AIC) was used to identify the most parsimonious model (Akaike 1974) and the AICc weight was used to provide a measure of the weight of evidence in favour of each model (MacKenzie et al. 2002).

Table 2: Summary results for multivariate backwards stepwise regression approach to model selection

Variables included in model	2Log likelihood	R^2	ΔAICc	AICc Weight	Hosmer and Lemeshow test		Variables removed
					X^2	p	
M0=Full Model	-73.93	0.71	7.67	0.018	1.34	0.99	
M1= VL, SD, PD, DC, DF, CS	-77.09	0.70	0	0.844	1.47	0.99	Landform, Density of Debris, Understorey Density, Canopy Cover, Vegetation Type, Grass Present, Distance to Creek
M2= VL, SD, DC, DF, CS	-81.100	0.68	6.01	0.042	2.19	0.97	Pig Damage
M3= VL, SD, DC, CS	-80.304	0.69	4.42	0.093	7.64	0.47	Distance to Fire Edge
M4= VL, SD, DC	-85.642	0.67	11.10	0.003	6.49	0.59	Canopy Scorch
M5= VL, DC	-91.02	0.65	19.86	0.00	17.24	0.03*	Sedge Dominant
M6= VL, SD	-125.77	0.51	89.36	0.00	9.59	0.01*	Distance to Canopy
M7= DC, SD	-143.75	0.44	125.32	0.00	9.78	0.01*	Vegetation Layers

Lower values for the Akaike Information Criterion (AIC) indicate a more parsimonious model; Higher values for the AICc weights indicate stronger statistical support for the models. Nagelkerke R-square (R^2), the maximum log likelihood ratio (-2Log likelihood), the Hosmer and Lemeshow goodness of fit test (the model fits if p> 0.05, i.e. the model prediction is not significantly different from the actual observation). Refer to Table 1 for explanation of the variable codes. *M5, 6 and 7 results in a loss of GOF.

M1 is the strongest model, comprising 0.84 of the model weights. The fit of the model is considered satisfactory because the Pearson Chi-Square statistic is not significant (p=0.99). The removal of the variables sedge dominant (SD), distance to unburnt canopy (DC) and vegetation layers (VL) from the model led to the largest increases in the delta AICc value, loss of model weight and resulted in poorly fitting models. Removal of the variables of pig damage (PD), distance to fire edge (DF) and canopy scorch (CS) also resulted in significant increases in the delta AICc value (greater than 2 points) and a large reduction in the model weight, indicating that these variables are also significant in the model but perhaps not as significant as the afore-mentioned variables.

4. RESULTS

4.1 IMPACT OF THE FIRE ON KNOWN SUBPOPULATIONS

Of the 43 burnt sites known to be occupied by quokkas prior to the fire, only 10 of these (23%) were occupied post fire and seven of these were immediately adjacent to the fire edge, adjoining unburnt vegetation (Figure 5). The remaining three sites were greater than 1 km within the fire area and isolated from the unburnt vegetation at the edge of the fire.

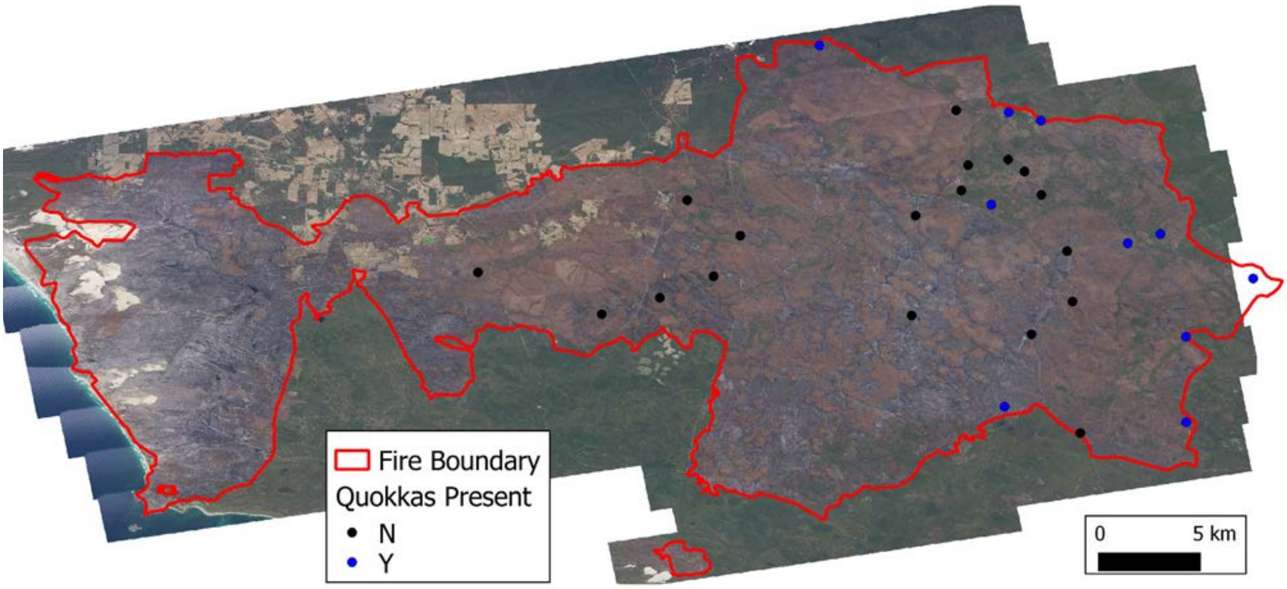

Figure 5: Post-fire occupancy of sites within the Northcliffe fire area. Only sites that were known to be occupied by quokkas prior to the fire are presented

Where animals were found occupying habitat greater than 1 km from the edge, they were doing so in small refuge patches where canopy and mid storey vegetation remained intact following the fire, or where a tiny pocket of riparian vegetation remained unburnt (Figure 6). In each of these cases, the vertical vegetation structure retained some level of complexity (three vegetation layers or more), which is a habitat feature that has previously been found to be important for quokkas in this region (Bain et al. 2015).

Figure 6: Examples of occupied 'refuge patches' inside the fire-affected area where a small number of animals have survived the fire. a) A small area of riparian system where Melaleuca/ Taxandria mid storey and Eucalyptus diversicolor over storey remained intact, and some individual *Gahnia decomposita* remained unburnt. The rest of the understorey burnt, but recovered quickly. b) An unburnt pocket of riparian system approximately 0.5 ha in size. c) A small linear patch of riparian system approximately 0.1 ha in size, where the mid storey remained intact, surrounded by mid slopes and ridgelines of karri forest where the mid storey was killed and the over storey was defoliated.

4.2 CURRENT PRESENCE OF QUOKKAS WITHIN AND SURROUNDING THE FIRE AREA

Overall, 127 sites were surveyed for the presence of quokkas including: 33 sites in the unburnt areas surrounding the fire and 94 sites within the fire area. A total of 46 sites were occupied at the time of this survey (Figure 7). The naïve occupancy rate for the unburnt sites adjoining the fire-affected area was 0.61 (uncorrected for detection probability). For burnt sites near the edge of the fire, the naïve occupancy rate was 0.40.
For burnt sites more than 1 km from the fire edge, the naïve occupancy rate was less than a third of the unburnt sites at 0.19 (Figure 8).

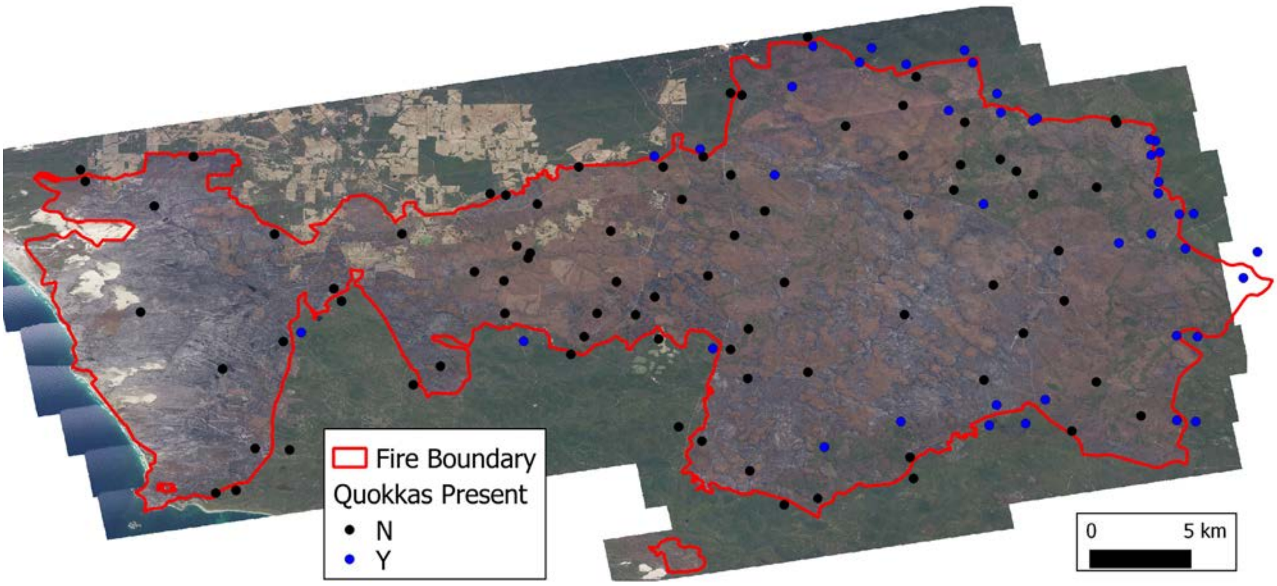

Figure 7: Post-fire occupancy of sites within and surrounding the Northcliffe fire area. All surveyed sites are presented.

Of the 26 occupied burnt sites, 18 were located near the edge of the fire and in these cases, scat deposition patterns were within 680 m (Mean=211 m, SE=30.6) of the unburnt vegetation surrounding the fire area. The remaining eight occupied sites within the fire area were located more than 1 km from the edge. This includes the four impact sites mentioned in section 4.1. As with the impact sites, animals occupying habitat more than 1 km from the edge were located in small areas where canopy and mid storey vegetation was left intact by the fire and/ or where a tiny pocket of riparian vegetation remained unburnt. In some cases these pockets were less than 0.1 ha in size and most were less than 0.5 ha. The furthest that faecal pellets were found from these internal refuge patches was 186 m (Mean 12.5; SE=4.1). There were 20 occupied sites in unburnt vegetation surrounding the fire area. The density of quokkas occupying unburnt sites was higher than that for burnt sites, with an average of 7.5 animals/ ha (Min=3, Max=22) in the unburnt sites that were occupied surrounding the fire area in comparison to an average of 3.9 animals/ ha in the burnt sites that were occupied within the fire area (Min=1, Max=11; Figure 9). The maximum density of quokkas in the unburnt sites of 22 quokkas/ ha was considered unusually high. Overall, a total of 39 quokkas were estimated to be seeking refuge within the internal refuge patches, a total of 73 quokkas were estimated to be using the burnt sites near the fire edge and a total of 306 quokkas were estimated to be occupying unburnt sites surrounding the fire-affected area. It is estimated that approximately 500 individuals were lost from the fire-affected area, based on the number of known occupied sites and the average sub-population size for this area. It is likely that some of these animals survived by fleeing the fire and are now surviving in the adjoining unburnt areas.

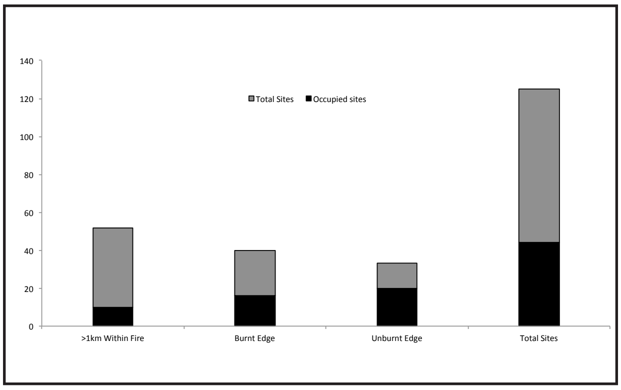

Figure 8: Location of occupied survey sites in relation to the fire edge. The naïve occupancy rate (ψ) is presented for each set of sites.

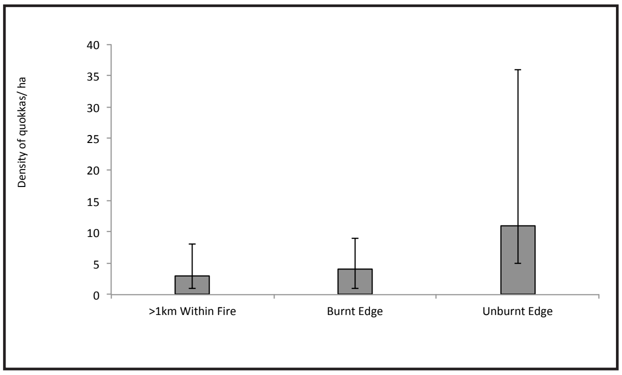

Figure 9: Density of quokkas in burnt sites near the edge of the fire, burnt sites >1km within the fire and unburnt sites surrounding the fire area. The minimum, lower quartile, median, upper quartile and maximum values are presented.

4.3 FACTORS DRIVING OCCUPANCY

The strongest model (model weight of 0.84) describes the number of vegetation layers (VL), the presence of sedges in the understorey (SD), the area of pig damage (PD), the distance to unburnt canopy (DC), the distance to the fire edge (DF) and the category of canopy scorch (CS) as having the strongest influence on occupancy of post-fire habitat by quokkas within the fire-affected area (Table 2).

Vegetation Structure

The probability of a habitat being occupied by quokkas was dependent on the structure of the vegetation and, in particular, the number of vegetation layers. The vegetation structure was variable throughout the surveyed sites, largely in response to the dominant ecotype, components of the midstorey and overstorey that survived the fire, and the rate of recovery of the understorey. Of the sites that were occupied, 100% contained habitat with three vegetation layers or more (maximum seven layers), while habitats with two or fewer vegetation layers were never occupied (Figure 10). Vegetation structure is a habitat feature that has previously been found to be important for quokkas in this region (Bain et al. 2015).

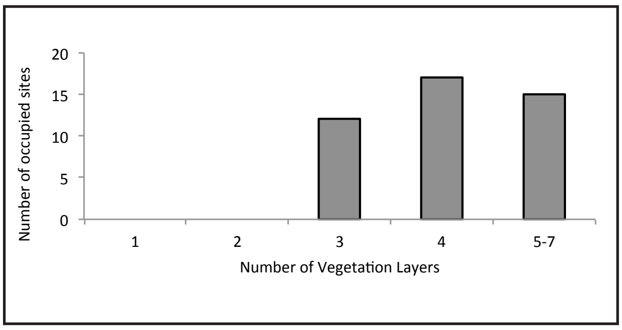

Figure 10: Occupancy patterns for quokkas in the Northcliffe fire area and surrounds, in relation to vegetation structure (number of vegetation layers) present

Canopy Scorch

Within the fire area, sites with some canopy left unburnt were more likely to be occupied by quokkas than areas with scorched or defoliated canopy. Sites with unburnt canopy had a naïve occupancy rate of 0.93; sites with scorched canopy had a naïve occupancy rate of 0.24; and sites where the canopy had been defoliated by the fire were always unoccupied (Figure 11).

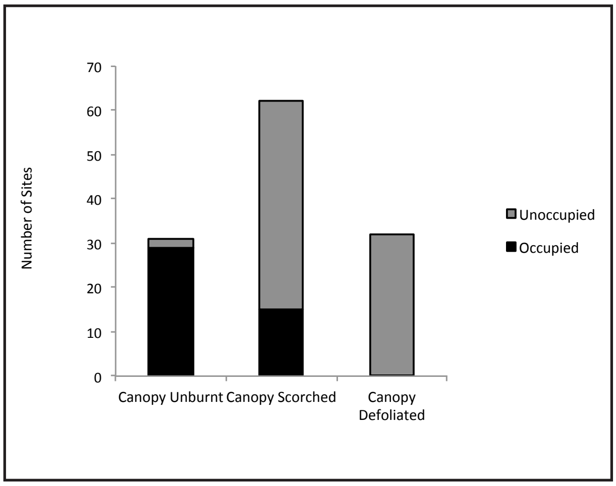

Figure 11: Occupancy patterns for quokkas in the Northcliffe fire area, in relation to relative levels of canopy loss following fire (unburnt, scorched and defoliated).

Feral Pig Damage

The wallowing and digging behaviours of feral pigs contributed to areas of altered soil structure, physical disturbance of vegetation that was recovering from the fire, and removal of seedlings, seed and lignotubers. A total of 26 sites contained pig damage, with damage ranging from isolated diggings approximately 1 m^2 in size, through to diggings that were more extensive and covered an area of more than 120 m^2. While quokkas were present in areas where pigs were active, sites were occupied by quokkas only where the damage caused by feral pigs covered an area that was less than 10 m^2 (Figure 12).

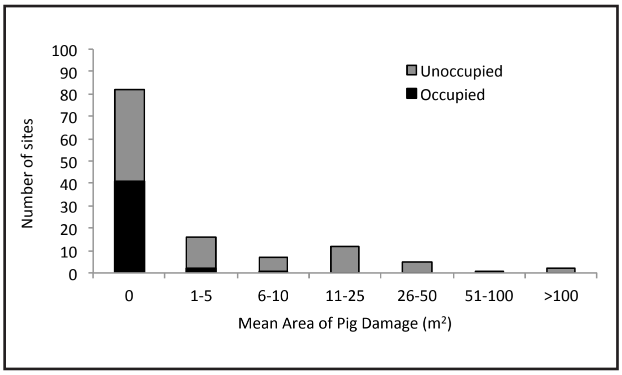

Figure 12: Occupancy patterns for quokkas in the Northcliffe fire area and surrounds, in relation to feral pig damage.

Sedge Understorey

Sites containing a sedge component (Restionaceae, Cyperaceae or Anarthriaceae) in the understorey were more likely to be occupied than sites where sedges were absent (Figure 13). In particular, the presence of fine sedges such as Empodisma gracillimum and Anarthria prolifera seemed to be important. Other common sedge species included: *Lepidosperma effusum*, *Lepidosperma tetraquetrum* and *Gahnia decomposita*. A total of 29 (66%) of the occupied sites contained a sedge-dominated understorey.

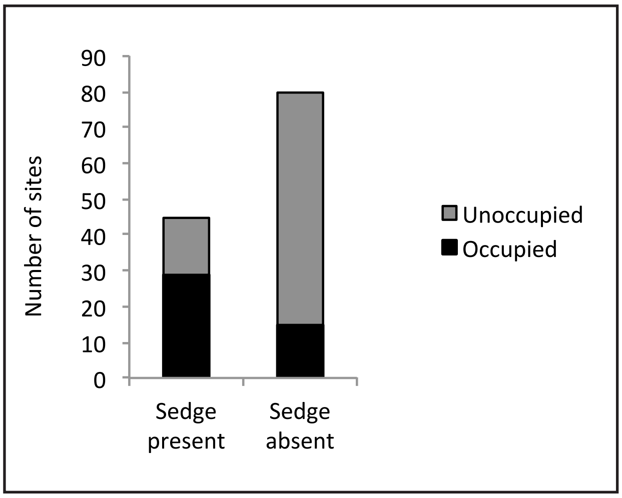

Figure 13: Occupancy patterns for quokkas in the Northcliffe fire area and surrounds, in relation to the presence of sedge species in the understorey.

Distance to Unburnt Canopy

Within the fire-affected area, habitat was more likely to be occupied by quokkas if it was within 186 m of unburnt canopy (Mean= 12.5 m, SE=4.1; Figure 14).

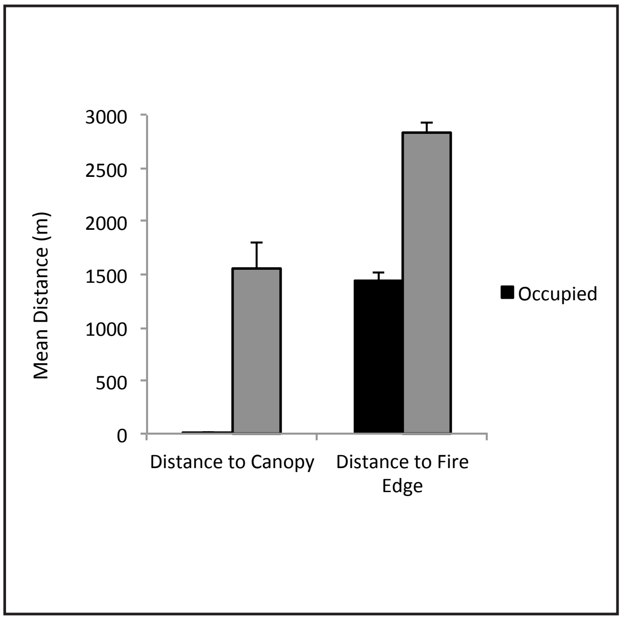

Figure 14: Occupancy patterns for quokkas in the Northcliffe fire area, in relation to the distance of sites to areas of unburnt canopy and to the edge of the fire.

Distance to the Fire Edge

The distance to the fire edge was also important and overall, the average distance of occupied sites to the edge of the fire was 1439 m (SE=248 m; maximum=11,439 m; Figure 14). This value includes the internal refuge patches that were isolated from the edge by large areas of burnt vegetation. Faecal pellet deposition patterns suggested that there was no movement of quokkas between these internal refuge patches and the edge of the fire-affected area. Distance to the fire edge is therefore likely to be even more significant if consideration is given only to the sites that were continuous with or connected to the unburnt vegetation adjoining the fire-affected area. In these cases, faecal material from quokkas was found a maximum distance of 630 m from the fire edge, but still within 186 m of unburnt canopy.

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5. DISCUSSION

5.1 IMPACT OF THE FIRE

Intense fire behaviour was recorded for the Northcliffe fire area throughout much of the time it was burning and this was associated with loss of vertical vegetation structure and homogeneous fire outcomes over a broad spatial scale (98,000 ha). The fire resulted in the loss of 33 known subpopulations of quokka, which equates to 77% of subpopulations known to be present in the area prior to the fire. At the time of this survey, all quokka activity within the fire-affected area was restricted to the edge of the fire or to a small number of internal sites where low densities of quokkas had been isolated from the edge in marginal and in some cases unsuitable habitat.

Where quokkas were using burnt habitat that was continuous with the fire edge, their densities were also low and faecal deposition patterns suggested they were not moving more than 630 m into the burnt area, and not more than 186 m from areas of unburnt canopy.

Where quokkas were occupying unburnt habitat adjoining the fire area, their densities were generally more consistent with what is considered average for this area. Previous studies have found quokka subpopulations in this region contain an average of 9 quokkas/ ha (Bain unpublished data). In one case however, an estimated 22 quokkas/ ha was recorded. This suggests that at least in some sites, the density of subpopulations has been augmented by animals that have been displaced from the fire-affected area. It is unknown whether such increased densities are sustainable, nor whether there is an effect of increased density on individual space use, resource use and social conflict.

5.2 FACTORS DRIVING OCCUPANCY

Quokkas most commonly occupied post fire habitats in the Northcliffe fire area, where there was a complex vegetation structure (3-7 layers of vegetation), a sedge dominated understorey, low levels of feral pig damage, and proximity to unburnt canopy (within 186 m). These findings are consistent with known habitat requirements for quokkas in this region (Bain et al. 2015) and can be linked to thermoregulatory requirements and predator avoidance behaviours that have previously been documented for this species (Kitchener 1981, Hayward et al. 2007, Bain et al. 2016).

Quokkas need diurnal shelters that aid their thermoregulation (Kitchener 1981). Multiple vegetation layers achieve this by providing insulation and protection from the elements as well as providing complexity in the vertical structure that increases opportunities for predator avoidance. Sedges in the understorey are indicative of moist conditions and are often the first and most rapid element of the vegetation to recover following fire, providing an important insulative layer in the habitat. Sedges also tend to form a dense understorey layer that provides opportunities for predator avoidance, reduces the hunting efficiency of introduced predators, and reduces the availability of substrate for feral pig disturbance.

Feral pig activity is particularly destructive in moist environments following fire, when the substrate is exposed. Their digging and wallowing activities reduce the structural complexity and density of the vegetation through physical disturbance of the soil profile, removal of regenerating seedlings, lignotubers and seed, and disturbance to established vegetation. This has previously been demonstrated throughout Australia (Choquenot et al. 1996, Hone 2002, Burnside et al. 2012, Adams 2014). Such changes to the vegetation structure may also make habitats more accessible for introduced predators such as foxes and feral cats.

Increased distance from unburnt vegetation has previously been associated with an increased risk of predation for many small and medium sized herbivores (Banks 2001; Le Mar and McArthur 2005; Styger et al. 2011; Bain et al. 2016). Where predators are present, quokkas tend to limit their movements to areas that are proximate to a safe refuge (Bain et al. 2016). In this study, occupied areas always occurred in conjunction with unburnt canopy. Unburnt canopy was generally indicative of lower intensity fire, which resulted in a higher likelihood of small unburnt patches, complex vegetation structure from surviving midstorey and overstorey components, and rapidly recovering understorey.

5.3 RECOLONISATION

The surveys undertaken in this study occurred one year following the fire and there is evidence of some movement of quokkas back into the burnt areas; however, movement seemed restricted to the edges, less than 186 m from unburnt canopy or 630 m from the fire perimeter. This is consistent with findings in Bain et al. (2016), where quokkas did not venture further than 230 m from unburnt pockets in the first 12 months following a prescribed burn.

These small, isolated groups of quokkas are likely to be critical for the recolonisation of core areas of the fire, however the refuge patches they are occupying are in most cases smaller than 0.5 ha and surrounded by intensely burnt ecotypes. This makes animals surviving here highly vulnerable to factors such as predators and weather, with an increased risk that they may not survive to recolonise areas further afield.

A large proportion of previously occupied habitats within the fire area are now unoccupied and many of these areas are up to 36 km from areas that are currently occupied by quokkas. Quokkas in the southern forest have the ability to move large distances and have been recorded moving distances of up to 14 km within a riparian system to reach new habitats (Bain 2015). Emigrations across much larger distances are therefore possible, where habitats are suitably connected.

The ability of quokkas and other species to either disperse through the burnt landscape or use refuge patches as 'stepping stones' is important in maintaining habitat connectivity and movement patterns at a landscape scale (Templeton et al. 2011; Driscoll et al. 2012). In the absence of such patches and movement corridors, recolonisation of these core areas may be significantly delayed. Similarly, additional disturbances that contribute to an increase in the distance between suitable habitat patches could also contribute to these core areas remaining unoccupied. This could in turn contribute to a disruption of metapopulation function, through lack of movement between subpopulations fragmented by the fire.

In previous studies for this species, intensely burnt wildfire areas were not recolonised for four years (Bain et al. 2016). Given the scale and intensity of the Northcliffe fire area, four years would be expected to be the minimum period required for habitat to recover to a point where quokkas are not limited by their proximity to unburnt vegetation. Additional survey work over the next few years will help to build a clearer understanding of recolonisation patterns and whether movement of quokkas is occurring into the core of the fire-affected areas.

5.4 MANAGEMENT IMPLICATIONS

Australian fauna is adapted to fire, but the scale and intensity of fire is important and has implications for the long term suitability and connectivity of habitat, as well as for metapopulation function. Large-scale and homogenising wildfires are becoming more frequent as a result of drying climate, drier and more combustible vegetation, a higher prevalence of summer lightning strikes and increasing populations in the rural-urban interface (DFES 2015). This creates challenges for the protection of habitats that are important for threatened species and the maintenance of landscape level habitat diversity and connectivity, in a manner that is consistent with human protection requirements.

Following a disturbance such as the Northcliffe fire, other threatening processes such as prescribed fire, timber harvesting, introduced predators, feral pigs and climate change stressors have the potential to have a cumulative influence on survivorship, mortality, habitat connectivity and population viability for threatened species. An integrated approach towards the management of these threatening processes is likely to be important for protection of key habitats and metapopulation function for quokkas as well as for broader species conservation outcomes.

The following is a summary of the main management implications arising from this study:

- The internal refuge patches are likely to be critical for the recolonisation of core areas of the fire, however there is a low likelihood that individuals sheltering in these refuge patches will survive without an integrated approach to threat management and habitat protection.
- Predators focusing on refuge patches for hunting may reduce opportunities for internal recolonisation by killing any fire survivors and recolonising individuals attempting to establish new colonies.
- Feral pigs may modify vegetation structure within the fire-affected areas, so rendering the habitat unsuitable for quokkas in the long-term.
- Given full recolonisation of the fire area by quokkas is not expected for at least four years, prescribed fire or harvesting activities applied within and adjoining the fire-affected area within this period may increase the area of unsuitable habitat, increase habitat fragmentation and may even force animals displaced by the fire back into the fire-affected area before the habitat is suitable.
- The high density of animals concentrated in some habitats surrounding the fire may be unsustainable. It is important that these areas are monitored, the habitat protected and connectivity between these areas and other areas outside of the fire maintained until such a time as animals are able to successfully emigrate back into the fire area.
- A large proportion of the core of the fire-affected area is currently unoccupied and will need to be recolonised by quokkas from the internal refuge patches or from the edges of the fire. It is important that these areas are managed to ensure that habitat connectivity is re-established and maintained. Where natural movement has not occurred within six years, intervention may be required to maintain metapopulation function, particularly where additional disturbances are planned such as prescribed burns.
- Management effectiveness is limited by lack of knowledge. For example, there is currently limited knowledge of the factors limiting survival and recolonisation of quokkas following intense and broad-scale fire; the impact of introduced predators on the survivorship of quokkas in the fire area; the impact of feral pigs on vegetation structure and habitat quality; the carrying capacity of habitat and how this is affected by an influx of individuals following a fire of this scale; and the effects of the fire on sympatric species.

5.5 COMMUNICATION AND INTEGRATION OF OUTCOMES

This study has important implications for the management of habitat for threatened species following broad-scale and homogenising wildfire events such as the Northcliffe fire. Communication of the main outcomes of the project and project recommendations are an important part of raising awareness, integrating knowledge into operational activities and improving management effectiveness.

The steering committee has identified that a communications plan will be prepared for this project to facilitate communication of outcomes to all relevant stakeholders groups, land managers and the broader community. Some tactics for consideration in the plan include: presentations at conferences or community sessions, the development of community education and public information packages and/ or displays, joint media initiatives, the review of existing fire management guidelines, preparation of map products and/or mapping layers for fire and conservation planning. The communications plan will be prepared as a separate document to this report.

In addition, this report provides recommendations regarding management activities, research priorities and operational priorities that will build on the outcomes of this project and further improve our understanding of the effects of intense and broad-scale fire on threatened species, such as the quokka (Section 6).

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6. RECOMMENDATIONS

The implementation of the following recommendations will contribute to the protection of habitats that are important for quokkas within and surrounding the Northcliffe fire area, the restoration of landscape level habitat connectivity, the maintenance of metapopulation function, and an improvement in knowledge essential for effective management of this species.


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Key recommendations for action include:

Project direction and context

- Clear project direction and focus.
  Develop a project plan that sets quantifiable objectives and ecological targets for quokka recovery within the Northcliffe fire-area, establishes priorities, establishes a clear monitoring, evaluation and reporting framework, identifies thresholds and triggers at which management action must be taken and provides a process for transfer of information and program improvement.

Threat mitigation and habitat management

- Manage further disturbance processes within and surrounding the fire that may compound the effects of the wildfire. For example, prescribed fire or harvesting activities applied to adjoining forest blocks within the next four years may increase the area of unsuitable habitat, increase habitat fragmentation and may even force animals displaced by the fire back into the fire-affected area before the habitat is suitable, so increasing their vulnerability to predators, weather and other variables.

- Manage threatening processes in an integrated manner to increase survivorship of quokkas and allow animals to move out of the refuge patches as the surrounding habitat recovers. In particular, introduced predators, feral pigs, prescribed fire and harvesting activities should be the focus of active management for at least the next four years.

- Identify key riparian systems that are likely to be important for connecting refuge patches and facilitating movement patterns for recolonisation, both within and surrounding the fire-affected areas. Protect these riparian systems from further disturbance activities (e.g. fire, harvesting, feral pigs) that may reduce their suitability as movement corridors.

- In the event that unassisted recolonisation of core areas by quokkas has not occurred within six years, consider the need for assisted recolonisation, where suitable habitat is present.

Research/ Adaptive Management

- Improve management by addressing knowledge gaps. Key knowledge gaps that require focus include:
  - Improve our understanding of recolonisation patterns by quokkas following large-scale fire events (population level). Specifically:
    - How long will the refuge patches continue to be important for quokkas as the surrounding areas recover?
    - How long does it take for quokkas to recolonise previously occupied sites at varying distances within the fire-affected area?
    - Are habitats within riparian systems more likely to be colonised before habitats outside of riparian systems? (Important for understanding the mechanisms of post-fire recolonisation and habitat protection priorities).
    - Are sites that were affected by lower intensity fire (canopy intact or scorch-level impacts) likely to be recolonised faster than sites that were affected by high intensity fire (defoliation)?
    - What are the other key factors driving occupancy and abundance patterns (e.g. vegetation structure, distance from the fire edge, feral pig damage, sedge understorey)

  - Improve our understanding of the factors limiting quokka recovery following a large-scale, homogenising fire (individual-level study that will inform population level management). Specifically:
    - How are quokkas within the fire area using habitat differently to those in unaffected areas (space use, habitat preference, movements)?
    - How are space use, habitat preferences and movement patterns related to refuge patch size, vegetation structure, food resources, water availability and feral pig damage?
    - Do quokkas exclusively use riparian systems to migrate between areas of suitable habitat?
    - What factors are driving mortality in the post-fire environment and how do these differ from what is happening in undisturbed habitat?
    - Do predators limit movement of quokkas out of refuge areas?

  - Quantify the impact of introduced predators on the recruitment, demography and abundance of quokkas in a post-fire environment.

  - Quantify the impact of feral pigs on vegetation structure and habitat quality

  - Develop an understanding of the carrying capacity of habitat.

  - Effects of large-scale, homogenising fire on sympatric species.

Communication and Partnerships

- Effective communication of the outcomes of this project and future directions to encourage integration of new knowledge into management, to facilitate community engagement and interest, to build professional collaborations, to increase project capacity and to improve management effectiveness.

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