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Immediate impacts of fire on koala movement in a fragmented landscape

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A B S T R A C T

Hazard reduction burns could pose a significant conservation challenge to threatened habitat specialists, such as koalas *Phascolarctos cinereus*. This study examines the immediate effects of a medium to hot hazard reduction burn on a small number of koalas occupying a fragmented agricultural area. Three koalas being monitored using GPS telemetry were inadvertently exposed to fire in a small strip of roadside vegetation in an agricultural landscape, providing an unexpected opportunity to assess their immediate responses to the fire. Nearly 81 % of available trees were burnt to some degree, with 31 % of tree foliage scorched up to 10.2 m above the ground. The koalas reduced their home range sizes by 20–54 % post-fire, where two avoided burnt areas while one remained within them. These findings highlight the importance of maintaining unburnt patches and corridors in fragmented landscapes and developing comprehensive conservation plans to mitigate the adverse effects of fire on koalas and other arboreal fauna.

1. Introduction

Fire is a strong ecological force that can produce a variety of direct and indirect effects, which may vary based on the extent and nature of the fire, and the ecology of the affected species (Kelly et al., 2020; Prestemon, Pye, Butry, Holmes, and Mercer, 2002). The risk of wildfire is also exacerbated by climate change, which will put more animals at risk in the future (Di Virgilio et al., 2019; Kelly et al., 2020). Accordingly, the prevalence and intensity of natural and hazard-reduction fire events are on the rise globally (Abatzoglou, Williams, and Barbero, 2019; Bowman et al., 2020), including in Australia, Africa, and the Americas (Canadell et al., 2021; Lindenmayer and Taylor, 2020; Xiang, Xiao, Feng, and Ma, 2023).

Hazard reduction fires that burn slowly across the ground without disturbing the vegetation canopy (e.g., low groundcover fires) are often used intentionally to reduce the risk of uncontrolled and relatively hot wildfires that burn all the vegetation, including the canopy (Burrows and McCaw, 2013). Some wildlife will preferentially use burnt habitat (Harper, Ford, Lashley, Moorman, and Stambaugh, 2016; Parkins et al., 2019), though others may die or be injured during wildfires (Jolly et al., 2022). Injuries such as pulmonary oedema and footpad burns can become life-threatening to some wildlife after the immediate danger has subsided (Baek et al., 2023). Wildlife remaining in burnt areas may experience a range of effects including pain, distress, interruption of daily

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movements and loss of food and shelter (Lindenmayer et al., 2013; Nimmo et al., 2019). They have also been observed to change their behaviour, movement, and habitat use patterns in response to fire events (Lindenmayer et al., 2013; Nimmo et al., 2019). Affected individuals can either abandon burnt habitat for a time after the fire (Chia et al., 2015; Harper et al., 2016) or adapt to changes; failure to do so may result in reduced fitness and poorer well-being in the long term (Nimmo et al., 2019).

Lack of connectivity could further force affected animals to remain in poor-quality habitat (Chia et al., 2015; Lefoe, Rendall, McKinnon, and Whisson, 2022), exposing them to increased predation risk due to the loss of cover (Geary, Doherty, Nimmo, Tulloch, and Ritchie, 2020). Given their specific habitat requirements, arboreal species may be especially affected by such events (Campbell-Jones et al., 2022; Mendonça et al., 2015) when 'ground fires' are intense enough to burn the canopy, making it unavailable or less suitable for foraging and resting (Lindenmayer et al., 2013; Mendonça et al., 2015). While the direct effects of fire on terrestrial fauna are most often studied, the indirect effects of fire on arboreal fauna have received less attention. We aimed to study the immediate effects of a hazard reduction burn on movement and space use patterns of one such arboreal mammal – the koala *Phascolarctos cinereus*.

The koala is a specialist arboreal folivore distributed along the east coast of Australia where hazard reduction burning is common (Ward et al., 2020). The home range sizes of this marsupial vary depending on the availability of food trees, habitat composition, and population density (Melzer, Cristescu, Ellis, FitzGibbon, and Manno, 2014; Moore and Foley, 2005). This species is threatened principally by ongoing habitat loss and fragmentation, predation, disease, fire, and climate change (Allen et al., 2016; Ashman, Watchorn, and Whisson, 2019; Gentle et al., 2019; McAlpine et al., 2015). Despite a specialised diet, koalas inhabit a wide range of habitats with diverse tree compositions dominated by Eucalyptus species (Adams-Hosking, Moss, Rhodes, Grantham, and McAlpine, 2012; McAlpine et al., 2023). There have been records of koalas occupying fire-burnt habitats (Chia et al., 2015; Matthews, Lunney, Gresser, and Maitz, 2007, 2016; Phillips, Wallis, and Lane, 2021), which could be due to improvement in the nutritional content of some eucalypt foliage (Lane, Youngentob, Clark, and Marsh, 2023). Low severity fire covering large areas could have less effects on koalas allowing them to stay in burn habitat (Johnson and Shapcott, 2024; Law et al., 2022). None of these studies have reported the immediate effects of fire

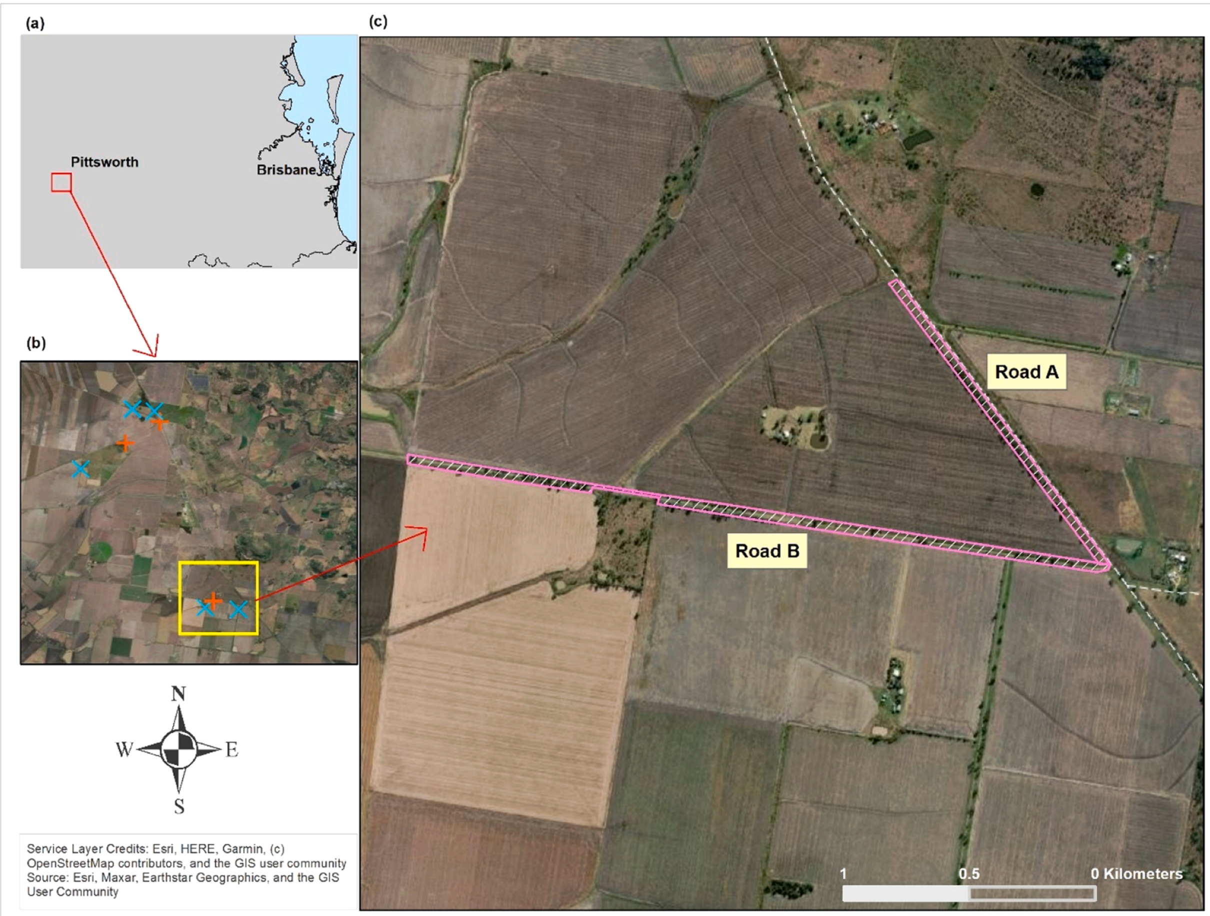

Fig. 1. Study area. (a) The inset shows the study area in the red box. (b) Location of nine koalas including males (marked with red), and six females (marked with sky blue), where fire occurred only in some areas to the south (highlighted with yellow box). (c) The burnt area is demarcated within the hatched purple box along roads. Both sides were burnt along Road B, while fire occurred on only the western side of Road A. The adjoining rectangular 9 ha patch of trees adjacent to Road B remained unburnt.

on koala movement and space use, nor do we know how koalas are affected by hazard reduction burns, especially ones in fragmented agricultural areas. Such studies are also lacking for other arboreal mammals like red pandas (Karki et al., 2021) and sloths (Silva et al., 2020).

Here we describe the immediate effects of an unexpected hazard reduction burn on a small number of koalas occupying a fragmented agricultural area. Using GPS telemetry, we assessed their space use and daily movement patterns in the few weeks before and after the fire in an effort to understand individual koalas' reactions to the fire. Given their dietary specialisation, we hypothesized that koalas would alter their movement and space use patterns. Fire could damage trees and impair the availability and quality of forage making such areas less suitable for arboreal mammals (Banks, Knight, McBurney, Blair, and Lindenmayer, 2011; Matthews et al., 2007). Therefore, we predicted that koalas would abandon burnt trees and limit their space use in the unburnt habitat where they would adapt to small areas and travel less distance.

2. Materials and methods

2.1. Study site

The study site was located in the Pittsworth region, approximately 160 km west of Brisbane, Queensland, Australia (Fig. 1), which is characterized by broad-scale cropping throughout the year. This region receives 696 mm (328–1252 mm) average annual rainfall, with a mean maximum temperature of 24 °C (17– 30 °C) and a mean minimum temperature of 11 °C (5– 17 °C, www.bom.gov.au). Koala habitat in this region is sparse and mostly linear along road corridors, with some very small patches of eucalypt and brigalow (*Acacia harpophylla*) woodland vegetation on private land.

2.2. Data collection and processing

We began a long-term koala monitoring program in this area in early 2023, which included capturing koalas and fitting them with GPS collars - Ceres tags (www.cerestag.com) to track their movements. The Ceres tags were expected to continuously transmit 3–6 GPS points per day. During the monitoring program a prescribed hazard reduction burn was conducted in roadside vegetation along two roads on 21 August 2023, covering a length of nearly 3.75 km and a width of 10 m on the burnt sides (Fig. 1). Three GPS-tagged adult koalas were resident in trees along these roads at the time - Michelle (female), Anne (female, with a dependent joey), and Chadwick (male). This fire occurred without our prior knowledge, but it created an opportunity to assess how these three koalas responded to the fire.

To assess the severity of the fire we counted all burnt and unburnt trees (diameter at breast height DBH > 10 cm) along both roads and estimated their height using a laser range finder, enabling us to estimate the proportion of the canopy that was scorched by the fire. Because we were only interested in the immediate effects of the fire, we arbitrarily included only GPS collar data from 35 days before and 35 days after the fire. For comparison, we also assessed another six koalas (two males and four females) inhabiting similar habitat nearby (Fig. 1), which was not burnt during that period. These habitats, comprising mainly road-verge vegetation dominated by *Eucalyptus populnea,* are located 6.5 km apart.

2.3. Data analyses

To filter erroneous GPS records we initially retained records within 5 m accuracy. We continued filtering records for the distance analysis by retaining more than two records from each animal for a 24 h period in the move package (Kranstauber, Smolla, and Scharf, 2023). Home range sizes were estimated within 95 % contour lines with upper and lower bounds of 95 % as confidence intervals (CI) using the autocorrelated kernel density estimation (akde) function in the ctmm package (Fleming and Calabrese, 2023). Using the occurrence distribution plots, we produced heat maps for pre- and post-fire events of all koalas. The difference in daily distance travelled between pre- and post-fire phases was examined for six koalas living outside the burnt habitat using a Wilcoxon-signed rank test (V) given the data had a non-normal distribution. A paired t-test (t) was used to assess the effect of fire on koalas' home range sizes. The outlier was addressed by replacing the extreme value with the nearest non-outlying value. Considering the small sample size (n=3), we did not consider these tests for koalas residing in the fire-burnt habitat. All the analyses were undertaken in (R Core Team, 2023).

3. Results

3.1. Effects of fire on vegetation

A total of 605 trees >10 cm DBH were present within the home ranges of the three koalas exposed to fire, including 372 trees along Road A and 233 along Road B (Fig. 1). The mean height of trees was 11.6 ± 2.7 m. These included four tree species, with *E. poplunea* (poplar box) as the dominant tree (71.4 %), followed by *Geijera parviflora* (22.4 %), *Acacia* sp. (4.5 %), and *Corymbia tesselaris* (1.7 %). The canopy foliage of approximately 81 % of trees was burnt to some degree along these roads, with a higher percentage of burnt trees along Road B (94 %) compared to Road A (73 %). When burnt, approximately 31 % of the available foliage was scorched up to 10.2 m above the ground (Fig. 2a), and at least 10 mature trees along Road A were subsequently killed and felled by the fire after it had continued to burn inside their trunks for several weeks (Fig. 2b–c).

3.2. Effects of fire on koalas

Chadwick was in trees along Road B when the fire occurred and moved a total of 364 m on that day, where he was living for five days (16–20 August) before the fire. He moved to trees in the unburnt patch adjacent to Road B on the day of the fire and stayed there for 18 days before revisiting the burnt trees on 9 September, where he spent two days and then returned to trees in the unburnt patch.

Anne was in a large poplar box tree along Road B when the fire occurred, and she moved a total of only 43 m on that day. She was in trees on this road for six days (15–20 August) before the fire, and moved to trees in the adjoining unburnt patch after the fire where she stayed for 22 days before returning to trees in the burnt area on 13 September. She spent only a day there before returning to trees in the unburnt patch.

Michelle was in a poplar box tree along Road A when the fire occurred, and she moved a total of only 34 m on that day. She was in trees along this road for four days (17 August) before the fire, remained there after the fire, and did not move to an unburnt area until 18 September (28 days later). She then moved to trees in the burnt area of Road B, and stayed there until 21 September before returning to trees in the burnt area of Road A.

3.3. Daily distance and space use patterns

A total of 2909 GPS records were available for these three koalas during the study period, but filtering resulted in a total of 2809 records being used for analyses (Table S1). The koalas exhibited varying movement patterns (Fig. 3). Chadwick moved 39 % less distance each day after the fire than before (pre-fire 196 ± 165 m), while Michelle (pre-fire 133 ± 236 m) and Anne (pre-fire 95 ± 86 m) moved 15 % and 45 % more, respectively, after the fire than before (Table S1, Fig. 3). Their space use pattern also varied after the fire (Fig. 4). Chadwick (pre-fire 11.8 ha) and Anne (pre-fire 9.5 ha) mostly avoided using the burnt habitat and reduced their home range by 20 % and 32 % respectively, while Michelle stayed in 54 % less space compared to her home range size before the fire (14.3 ha). She used an area along the road where most of the trees were burnt, but avoided areas with trees having completely scorched canopies.

By comparison, the mean home range size of the six koalas outside the burnt habitat was higher after the fire event (pre-fire: 13.3 ha (5.3–26.2 ha); post-fire: 29.9 ha (11–60.7 ha); $t = 2.7$, $df = 5$, $p = 0.04$, Table S1). However, their daily travel distance did not vary (pre-fire: 142 ± 124 m; post-fire: 189 ± 267 m; $V = 9010$, $p = 0.2$, Table S1). We also observed sex-specific variations in movement and space use patterns, with males travelling longer distances and occupying larger home ranges than females (Fig. S1a–b).

Fig. 2. Burnt trees in the study area. (a) Trees along a road with scorched canopy. (b) Tree trunk with burnt interior. (c) Fallen mature tree after the fire.

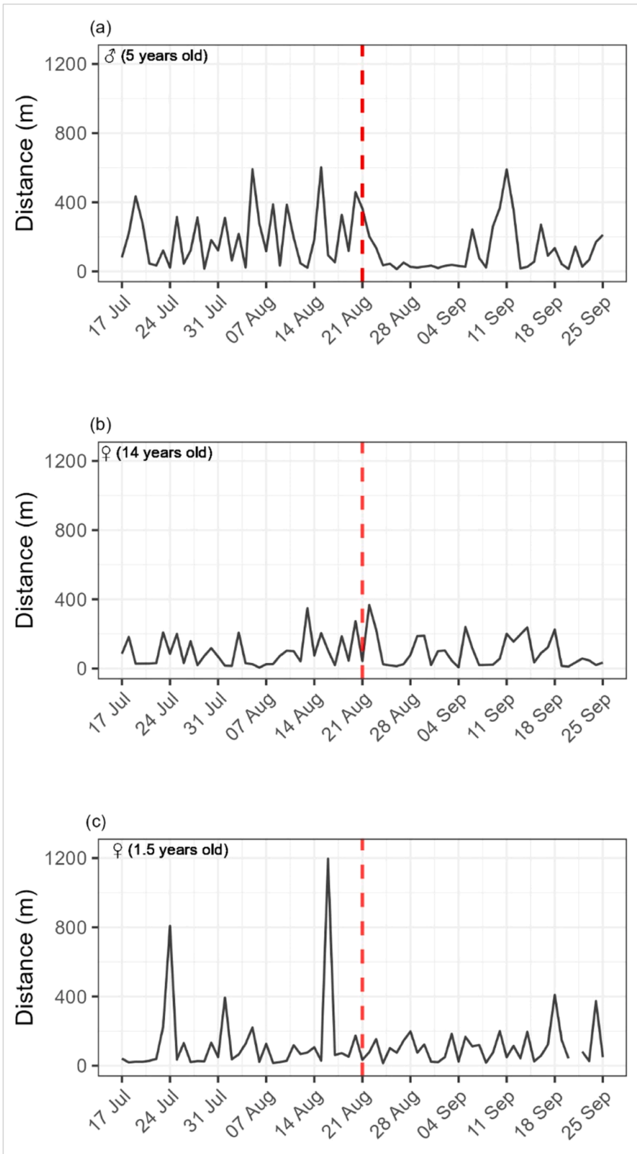

Fig. 3. Daily distance coverage. The line graph shows the daily distance covered by koalas. The red line demarcates the fire event date with the area on the left and right representing pre- and post-fire dates. (a) Chadwick, (b) Anne, and (c) Michelle.

4. Discussion

Fire can have profound effects on habitats and their constituent species, but little is known about the immediate effects of fire on arboreal species such as koala. Our assessment of koala responses to a fire in a fragmented agricultural landscape suggests that koalas reduce their home range size immediately after the fire (Table S1). Despite this, all koalas survived, and some did not even move out of the burnt area. The fire scorched almost all the tall trees available and killed and felled several mature poplar box trees preferred by koalas, temporarily destroying nearly one-third of the critical habitat and food available to them (Fig. 2). Though our sample sizes are small and opportunistic, these observations yield valuable insights for the conservation and management of this iconic species and its habitat.

The findings align with our hypothesis that koalas would alter their space use and movement patterns following the fire, though some variations were observed at the individual level. Of the three koalas, two individuals moved less than 45 m on the day of the fire (Fig. 3), suggesting that the presence of the fire hardly permit them to explore more trees. One koala seemed to have escaped the fire, which is evident from longer distances travelled during the fire event than during the pre- and post-fire periods. The two koalas living on Road B moved to the adjoining unburnt patch where they spent most of their time after the fire (Fig. 4). Given the size of that patch, which is nearly equal in total size to their pre-fire home range, they did not need to move further to forage after the fire. Besides, they

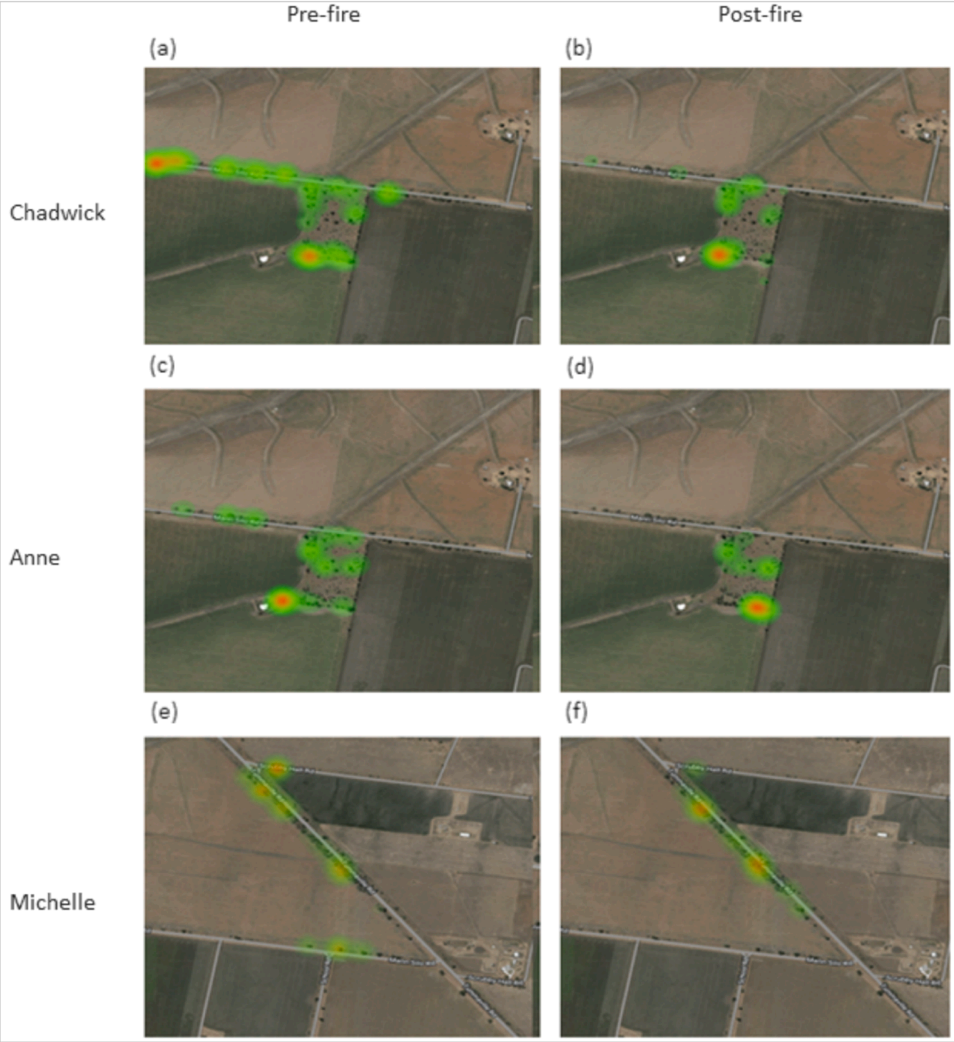

Fig. 4. Heat maps of the habitat use. The habitat use intensity increases from green to red. Pre- and post-fire tree use of three koalas are presented on left and right columns respectively: Chadwick (a–b), Anne (c–d), and Michelle (e–f).

had access to adjoining burnt trees with some canopy intact. In contrast, the koala living on Road A visited many more trees than before the fire, likely needed to meet her daily food requirements. This may explain the greater distances she travelled after the fire (Table S1).

Increased use of unburnt areas by the two koalas on Road B (Fig. 4) highlights the importance of such areas after the fire as refugia (Chia et al., 2015). Fire reduced the availability of food as approximately 13 % of the tree canopy was scorched on this road. Furthermore, the remaining leaves on trees may have had less moisture available for the short term (Bär, Michaletz, and Mayr, 2019). Other studies have reported that the quantity and quality of diet and cover is reduced on burnt trees, which may force animals to abandon such trees in the short term even though all the foliage was not burned (Law et al., 2022). However, the koala on Road A continued living on relatively large trees in the burnt area and avoided smaller trees that were used pre-fire, where nearly 40 % of foliage was scorched. There were a few unburnt poplar box trees (n=25) on the other side of Road A, and available farther away from her range (~500 m). However, she rarely used those trees, which was unexpected given koalas usually utilize roadside vegetation and scattered trees on such landscapes (Barth et al., 2020). Nevertheless, her preference for the relatively less damaged area with tall trees suggests that she was capable of surviving in the burnt area, at least temporarily.

Increase in home range size and space use patterns (Fig. S2) were evident after the fire for the other six koalas inhabiting nearby unburnt areas although their daily travel distance did not vary. These patterns were consistent with the view that fire negatively affected the three koalas exposed to fire. The seasonal phenomena due to breeding activities could have contributed to this variation in space use (Ellis, Melzer, Carrick, and Hasegawa, 2002).

Our results illustrate that medium to hot hazard reduction burn can still have substantial impacts on canopy vegetation, and on threatened arboreal species occupying that vegetation. Consideration should be given to establishing a threshold for wind speed and temperature, which, if exceeded, mean that such burns should not be implemented. The study has helped to understand potential impacts so that they can be better assessed to mitigate any adverse effects in the future. Considering the availability of limited refuge habitat, safe corridors and connectivity appear paramount to reducing the threat of fire impacts on native fauna in these fragmented landscapes. Planning the timing of burns, creating fire breaks, burning small patches, and conducting relocation or spotter-catcher activities, could each be critical in such landscapes. Additionally, laws, regulations and policies that permit hazard reduction burns and other forms of vegetation removal in fragmented habitat with threatened species may need revision if the conservation of the threatened species is a priority for regulators.

This study has provided some insights into the immediate response of an arboreal mammal to fire. However, greater sample sizes and further study are necessary to see how general these observations are in other areas. We also suggest several hypotheses for further investigation.

1. Forage quality of epichromic leaves of some burnt Eucalyptus species is improved after the fire (Lane et al., 2023; Marsh, Youngentob, and Clancy, 2021). Therefore, koalas are likely to return to the burnt habitat once the trees have recovered. However, the reduced density of trees, canopy cover, and available shelter may lead to an increase in home range size, daily travel distance, and activity patterns in the long term compared to pre-fire conditions.
2. Increasing fire frequencies have adverse effects on threatened species inhabiting such habitats, leading to a decline in population (Doherty, Macdonald, Nimmo, Santos, and Geary, 2024; Santos et al., 2022). We predict that koalas exposed to recurring fire events will experience elevated stress, poor health, and impaired breeding, affecting population demography in the long term.
3. Increased use of some unburnt patches could be detrimental to specialist species inhabiting fragmented habitats (Chia et al., 2015; Driscoll et al., 2021). In response to fire, koalas may move to unburnt patches, leading to an increase in their localised density. This heightened use could intensify competition for limited resources, temporarily extirpating them from such habitats where connectivity is absent.
4. Predation risk may increase post-fire due to loss in ground cover and reduced body condition of prey species (Doherty et al., 2022; Hradsky, Mildwaters, Ritchie, Christie, and Di Stefano, 2017; Leahy et al., 2016). We predict that koalas will experience an immediate increase in predation risk following the fire.

Exploring these hypotheses further will assist the conservation management of koalas across their extended range.

Ethical Statement

This study was approved by the Animal Ethics Committee of the University of Southern Queensland (ETH2024–0486), and the Department of Environment and Science, Queensland Government (Permit number WA0053507).

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authorship contribution

Conceptualization: DB, BA, GB, RB, PM; Investigation: DB, BA, GB, RB, KRS, PM; Formal analysis: DB; Writing – original draft: DB; Writing – review & editing: DB, BA, GB, RB, KRS, VG, PM.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e03274.

Data Availability

Data will be made available on request.

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