Movement Ecology

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Home ranges and movements of an arboreal folivore after wildfire: comparing rehabilitated and non-rehabilitated animals in burnt and unburnt woodlands

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Abstract

Background Wildfires can have complex effects on wildlife populations. Understanding how post-fire conditions affect the movement ecology of threatened species can assist in better conservation and management, including informing the release of rescued and rehabilitated animals. The 2019–2020 megafires in Australia resulted in thousands of animals coming into care due to injury or concerns over habitat degradation. This included hundreds of koalas (*Phascolarctos cinereus*), for which relatively little was known about how fire affected habitat suitability, or when rehabilitated animals could be returned to burnt areas.

Methods We compared the movements of koalas across three experimental groups–non-rehabilitated koalas in burnt habitat, non-rehabilitated koalas in nearby unburnt habitat, and rehabilitated koalas returned to their rescue location in burnt habitat in New South Wales, Australia. We GPS-tracked 32 koalas for up to nine months and compared, across treatment groups, home ranges, mean nightly distance moved, the farthest distance moved from their release site and total displacement distance.

Results We found no differences in koala movements and home range size between non-rehabilitated koalas in burnt and unburnt habitat. However, rehabilitated koalas moved farther from their release site, had larger displacement distances, and larger home ranges than non-rehabilitated individuals. Regardless of their experimental group, we also found that males moved further than females each night. Additionally, our resource selection analysis showed that, koalas preferred low and moderately burnt habitats over all other fire severity classes.

Conclusions Experimental frameworks that incorporate "treatment" and "control" groups can help isolate disturbance effects on animal movements. Encouragingly, despite catastrophic wildfires, burnt woodlands provided adequate resources for koalas to persist and recover. Furthermore, rehabilitated koalas re-integrated into the burnt landscape despite moving farther from their release sites than non-rehabilitated individuals. Studies like this improve our understanding of the ecological impacts of fire on species and their habitats, and will be instrumental in informing wildlife management and conservation efforts as wildfires increase in frequency and severity worldwide in response to climate change.

Keywords Wildlife rehabilitation, Habitat, Koala, Landscape disturbance, Endangered species, Conservation, Radio-tracking

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Introduction

Animals move through their environment to find and defend resources, disperse, breed, avoid predation, interact with conspecifics, and seek shelter [35, 109]. These essential movements normally occur within a defined area, which is often described as a home range [17, 23, 33]. Several intrinsic and extrinsic factors can influence home range size, including body size [76, 90], age [8, 121], sex [21, 44], food availability and quality [51, 89, 121, 125], climate [94, 117], and landscape fragmentation [44]. Understanding the factors that affect home range size can provide important information about the space and resources needed by species and populations, explain the drivers of movement patterns [130], and assist with conservation and management planning.

Landscape disturbance from natural and anthropogenic sources (e.g., fire, floods, land clearing, logging, etc.) can influence the structure of faunal and floral communities and can fragment landscapes by creating physical barriers to movement [37, 129, 155]. These can directly and indirectly affect how animals utilise and move within their environment [12, 100, 129, 146]. Fire is a common stochastic disturbance process in many terrestrial environments and can result in short-term effects on animal movement patterns due to the immediate emigration of individuals out of a landscape that are trying to escape fire fronts, and cause longer-term shifts in movement patterns within burnt areas due to changes in habitat suitability and altered competition and predation dynamics [42, 100, 146]. Changes in habitat suitability after fire can include the destruction or modified pattern of food and shelter availability. This can place substantial physiological stress on animals, which can negatively impact reproductive success, thermoregulation, and susceptibility to other threats such as predation and disease [26, 29, 31, 34, 57, 91, 97]. The ability to move and find resources in a burnt landscape can therefore affect the survival and recovery of individuals [59, 99, 100, 103, 144].

Past research into the effects of fire on home ranges shows considerable variation between mammal species. Some species show no change in home range size following wildfire [22, 82, 134, 138], while others expand their home ranges following fire [50, 54] or reduce them [105]. Increases in home range sizes have been attributed to easier movement through landscapes to find resources in the absence of understorey vegetation [54] or the need to move farther to find food if its availability is reduced [82, 133]. Where home range sizes were similar after fire despite a measurable change in resource availability, this has been attributed to individuals accessing one resource in burnt areas and another in adjacent unburnt areas [82]. The different responses reinforce the complex effects of fire on animal movements and home ranges and highlight the need to improve our understanding of the mechanisms that underly the varied patterns in wildlife population responses to fire.

The temperate forests of the south-east region of Australia are dominated by tree species of the *Eucalyptus* genus and are incredibly fire-prone [7, 14, 79, 119]. This region is also subjected to lower rainfall and hot dry summers, which are significant contributors to major wildfires [7]. From August 2019 to March 2020, extensive bushfires burned over 12 million hectares of eastern Australia [149]. These fires were unprecedented in both scale and severity [32, 73, 149]. Throughout this time, there were extensive wildlife rescue and rehabilitation efforts [38, 104]. One species that received particular attention was the koala. During the 2019–2020 fires, an estimated 60,000 koalas were killed or injured [136], and over 900 taken into wildlife care triage units [25, 80, 104].

Fire affects the distribution and abundance of koalas [26, 91], and could also influence short-term behavioural shifts in landscape use due to changes in population density, food quality and availability. Koalas, like many other animal species, form distinct home ranges, with males and females tending to overlap [28, 39, 56, 148]. Koala home range sizes can be influenced by a number of factors, such as the sex and age of the animal, population density, the availability and quality of feed trees, and by disturbance like fire [71, 78, 85, 113, 114]. Very few studies have investigated the effects of fire and rehabilitation on movements and home range sizes of the koala (but for exceptions see [81, 88]). Evaluating home range size after fire can provide insight into disturbance related changes in habitat quality, population health, and resilience, which can help to improve landscape and wildlife management [140, 141].

Understanding how rehabilitation in captivity may affect the longer-term recovery of individuals after fire is also important for decision-making around this type of intervention. Rehabilitation success is often determined by recovery and survival of animals in care to the point of release [81]; however, a better metric is survival post-release, which is not always monitored or recorded [53, 98]. Some studies have found that, after release, rehabilitated animals move farther than non-rehabilitated individuals, which may be due to several factors, including being displaced or even losing the skills to compete and survive following time in care [45, 47, 135]. Increased movements and dispersal can be energetically costly [13, 118], lead to increased exposure to predators [154] and mortality [47, 77, 118]. Post-release effects such as these could be exacerbated when the release environment has been affected by disturbance, such as fire [25]. For example, there could be greater conflict with non-rehabilitated individuals due to increased competition for limited food resources. Since fire severity and frequency in many parts of the world are predicted to increase with climate change [79], we need to improve our understanding of these post-release issues to effectively manage the reintegration of rehabilitated individuals into surviving populations of threatened species.

This study addresses identified knowledge gaps in managing wildlife living in landscapes impacted by fire, including the success of post-rehabilitation release [25]. The specific aim was to determine whether fire and/or rehabilitation affect the home range sizes and movements of koalas. We addressed this aim within an experimental framework, which is commonly lacking in these types of studies due to the stochastic nature of fire and wildlife rehabilitation [25]. We monitored koalas fitted with GPS collars across three treatment groups: 1) non-rehabilitated koalas in burnt habitat, 2) non-rehabilitated koalas in unburnt habitat, and 3) rehabilitated koalas released into their original burnt habitat. Each koala was monitored for up to nine months. Since severe fire can influence the availability of foliage biomass [58, 127], we expected that food resources would be diminished for koalas in the burnt landscape, resulting in them moving farther each day to obtain adequate nutrition and have larger home ranges compared to individuals in unburnt habitat. Because rehabilitated koalas had to reintegrate into the population in burnt habitat, where competition for resources may be increased, we also expected that they would have larger home ranges and movements compared to non-rehabilitated koalas.

Materials and methods

Study sites

The study was located in the New South Wales (NSW) Snowy Monaro Shire, a local government area in Australia spanning just over 15,000 km^2 and located approximately 130 km south of the Australian Capital Territory [49]. Much of the koala tracking work was located on the Macanally-Numeralla ranges. The area is on steep terrain, dominated by north-to-south facing ridges [102]. The elevation ranges from 800 to 1233 m above sea level [72] and the underlying geology is comprised of Palaeozoic Era sediments, with fluvial sandstones and lacustrine sediments amongst granite plutons and alkali basalts [86]. Overstorey vegetation is dominated by red stringybark (*Eucalyptus macrorhyncha*) and scribbly gum (*Eucalyptus rossii*), with ribbon gum (*Eucalyptus viminalis*) and candlebark (*Eucalyptus rubida*) more prominent in creek lines, and snow gums (*Eucalyptus pauciflora*) at higher elevations [102]. Brittle gum (*Eucalyptus mannifera*), broad-leaved peppermint *(Eucalyptus dives*), and apple box (*Eucalyptus bridgesiana*) were also common in some areas [1].

The Monaro Tableland, which encompasses the study area, is within a rain shadow zone [62, 102]. Prior to the fires in 2019, annual rainfall in the nearest city, Cooma, was 318.6 mm, which is well below the annual average of 528.1 mm [15]. Mean daily minimum and maximum temperatures in the Snowy Monaro Shire at these sites average 9 °C to 27 °C in summer, and −3 °C to 13 °C in winter [86].

The "burnt" site was burnt by wildfire in January 2020, with large areas of moderate to complete canopy loss (Fig. 3). The "unburnt" site was located approximately 15 km to the south and was not directly impacted by fire. Both sites were connected by continuous forest cover, and had similar tree species composition.

Koala groups

We used three treatment groups of koalas: 1) non-rehabilitated koalas in burnt habitat, 2) non-rehabilitated koalas in unburnt habitat, and 3) rehabilitated koalas released into the burnt habitat where they were originally rescued. The number of koalas in each group was a combined function of the available numbers of individuals and logistical considerations regarding tracking larger numbers of animals in multiple areas. The rehabilitated koalas comprised ten individuals that had been rescued from burnt habitat in the study area between early January 2020 and early March 2020 due to poor body condition and bushfire-related injuries. Rehabilitated koalas were released between June 2020 and November 2020. All rehabilitated koalas apart from a young, orphaned male were released at their capture location. The young male was housed and released with an adult female and her joey ~ 4.6 km from his capture location. Release timing depended on the overall health of each koala (subject to a health check–see "Health checks, collar fitting and release") and evidence that there was food available in

(See figure on next page.)

Fig. 1 Initial capture locations of all GPS-tracked rehabilitated koalas (green), and non-rehabilitated koalas in burnt habitat (blue) and unburnt habitat (red) (map data ©Google). Fire extent and severity mapping (FESM) [131] is also shown, with 2 representing the lowest severity (burnt understorey with unburnt canopy), 3 representing moderate (partial canopy scorch), 4 representing high (completed canopy scorch, ± partial canopy consumption) and 5 representing extreme (complete canopy consumption). The inset shows the location of the study area within south-eastern Australia

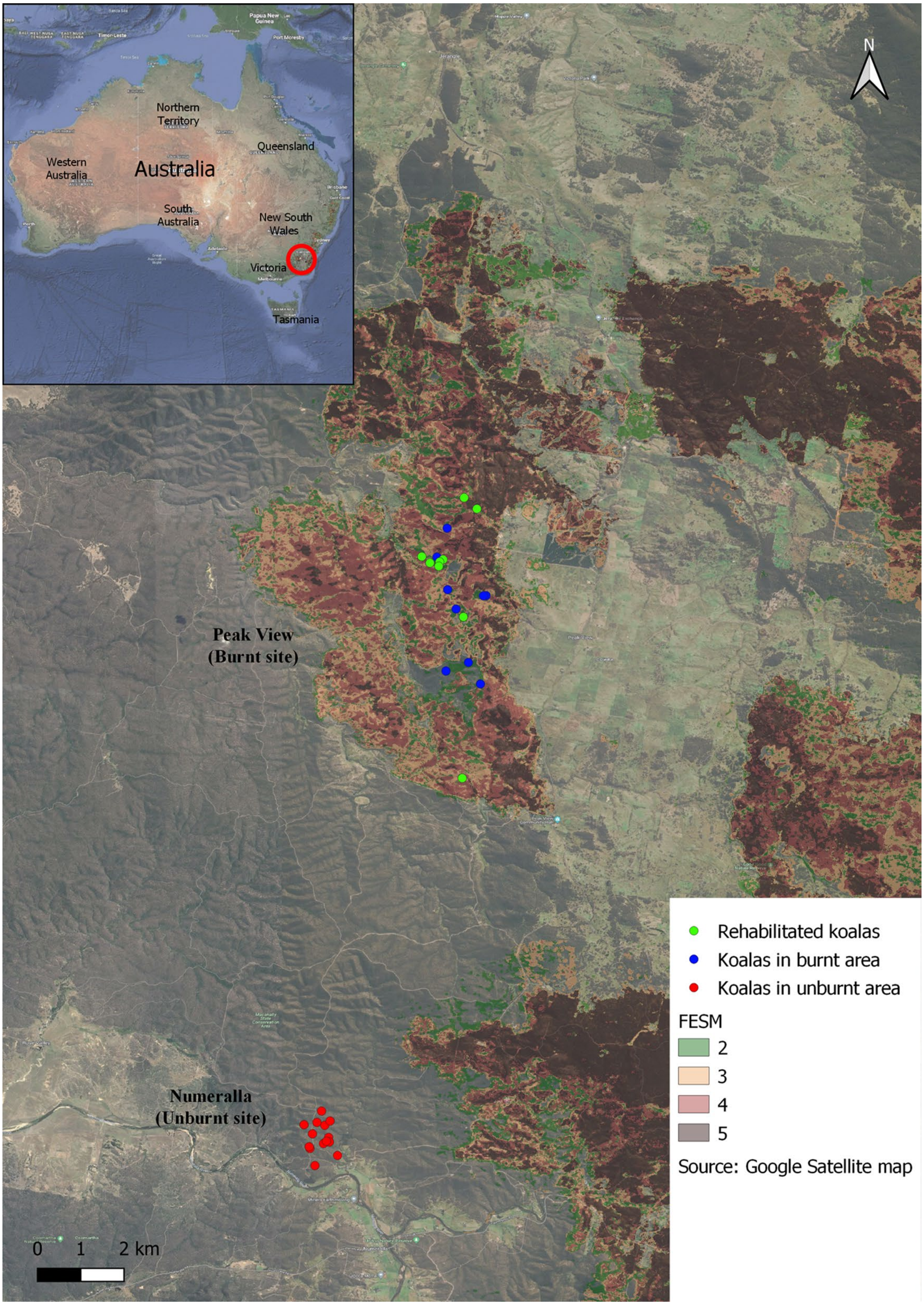

Fig. 1 (See legend on previous page.)

the area from which they were rescued (trees with intact canopy or producing new growth).

Non-rehabilitated koalas in burnt (n = 9) and unburnt landscapes (n = 13) were located between May 2020 and October 2020 using a combination of daytime ground-based searches and night-time thermal drone searches [150]. These koalas were captured using the noose and flag method [83], placed into canvas bags and transported by car (usually less than 1 km) for a health check by a wildlife veterinarian.

Health checks, collar fitting and release

Koalas in all three groups were given a health assessment under sedation by an experienced koala veterinarian immediately prior to being fitted with a GPS tracking collar and released [64]. The koalas ranged in age from < 2 to > 10 years old (based on tooth wear; [84]) and included 15 males and 17 females (Additional file 1).

While sedated, we fitted koalas with a Lotek LiteTrack 60 collar (Lotek Havelock North, New Zealand) with VHF and GPS capabilities. These collars weighed approximately 80 g each and had a "weak link" made of elastic that was designed to break under strain. Koalas were placed in a pet carrier covered with a towel in a quiet room to recover from sedation. All of the non-rehabilitated koalas from the burnt and unburnt landscapes were released on the same day of their capture, at their capture location.

Koala tracking and monitoring

Given that koalas are nocturnal, collars collected five GPS points per 24 h period at three-hourly intervals between 1900 and 0700 h for the duration of the study. This data was stored on the collars and could be downloaded remotely using a paired PinPoint Commander (Lotek, Havelock North, New Zealand). If there was no movement detected for 24 h, a mortality signal would activate.

We visually checked koalas daily for the first two weeks following the collar fitting, twice per week for the following two weeks, and then weekly when possible for the remainder of the study. Koalas were located using their unique VHF signal. Once a collared koala was located, we observed them with binoculars to check for any signs of injury, illness or decline of health. Occasionally, there were times when a koala could not be visually accessed at a scheduled point in time due to, for example, inaccessible roads or the koala had moved to a property that we did not have permission to access. When this occurred, we remotely downloaded their GPS data to check that their daily movements were normal (i.e., that they were moving around at night).

Collar removal

We removed collars from koalas after approximately nine months, unless the collar had already fallen off due to breakage of the weak link or slipping over the koala's head. Koalas were captured using the same noose and flag method, and received another veterinary health check under sedation [64]. Once recovered, koalas were released back into the same tree from which they were captured.

Home range calculations

In the context of this study, home ranges were defined as the area used by koalas (50% and 95% kernel utilisation distributions) across the entire period over which they were tracked before calculating home ranges, we cleaned the GPS data to remove points with poor spatial accuracy. We removed any points where the recorded altitude fell outside the range available at the sites because preliminary inspection revealed that these locations were invariably inaccurate. We then calculated the straight-line distance and difference in altitude between each GPS fix. If either difference was unlikely given the site and terrain, we removed the point. Finally, if the distance moved between consecutive points was greater than 200 m, we visually checked the location on a map relative to the previous and next point. In this case, we removed any points where a koala appeared to have moved to another location and then returned to the first at the following fix, because this scenario was unlikely. After this process, we further thinned the data to two GPS points per koala per night (22:00 and 07:00), to get the best spread and timing where koalas were most likely to have moved.

We calculated 50% and 95% kernel utilisation distributions (KUDs) for each koala using a bivariate normal kernel method in the *adehabitatHR* package (v0.4.19) [18] in R Statistical Software (v3.6.3) [112]. The *h* value (smoothing parameter), which controls the "width" or size of the kernel function around each point was set to the "reference" bandwidth defined as "*href*" [20]. We generated asymptotes from the *hrBootstrap* function in the *adehabitatHR* package to determine which koalas had a home range and which did not. Those koalas that did not have a home range were still moving significant distances, which suggest they had not 'settled' or were not in a defined 'range'. These koalas were not used in statistical comparisons of home ranges. Using the output from the analysis, we generated maps of home ranges in QGIS v.3.22.8 [110].

Calculation of movements

We calculated the nightly movement distance for each koala by adding the straight-line distances between each sequential GPS point between 1900 and 0700 h the following morning. We used these values to calculate the average nightly distance moved by koalas throughout the study, as well as the average nightly distance moved during different seasons. We calculated the displacement distance for each koala by measuring the straight-line distance between the point at which koalas were released after being fitted with a tracking collar and the location at which they either lost their collar or were recaptured. We calculated the greatest distance moved by measuring the farthest distance a koala was recorded from its initial capture location.

Resource use analysis

We used resource selection analysis to investigate whether koalas use habitat in different fire severity classes in proportion to its availability within their home ranges.

Using the *raster* package [55]in R and the NSW fire extent and severity mapping spatial dataset [131] we calculated the proportional availability of each fire severity class (as described by the State Government of NSW and Department of Planning and Environment 2020) within the home range of each koala that spent time in burnt habitat (n = 18). We also extracted the fire severity class at every GPS point used to generate home ranges, and calculated the proportion that fell within each of the five fire severity classes for each koala. We used the *compana* function in the adehabitatHS package [19] to perform a compositional analysis of habitat use [2], comparing proportional fire severity class use by each koala relative to the proportional availability of each fire severity class within their home range.

Statistical analyses

All analyses were performed using R Statistical Software (v3.6.3) [112]. We investigated whether home range size and movement data (displacement distance, greatest distance moved and mean nightly distance) differed between koala groups (rehabilitated, or non-rehabilitated in burnt or unburnt habitat), sexes or their interaction using ANOVAs. We also used an ANOVA to investigate whether mean nightly distance differed seasonally between male and female koalas. For greatest distance moved and displacement distance, all koalas tracked less than 50 days were excluded from analyses to avoid potential correlations between distance moved and the length of time tracked. We also excluded two female koalas from the non-rehabilitated unburnt group ('Rosalie' and 'Brandy') from all analyses because they moved from the unburnt habitat into burnt habitat during the study. Thus, their movements may have been influenced by characteristics of both unburnt and burnt habitat, and it was not appropriate to consider them within the unburnt group for comparative purposes. Despite this, their data are still interesting and could be informative, so we have included them descriptively in the results. Displacement distance, greatest distance moved, and 50% and 95% KUDs were all logged prior to analysis to achieve normal distribution. If results of the ANOVA were statistically significant ($p < 0.05$), we used the *emmeans* package (v.1.6.3) [75] to conduct pairwise t-tests to determine which treatments differed from the others ($p < 0.05$).

Results

Thirty-two koalas across the three groups were followed for between 9 and 256 days each (Additional file 1). Both rehabilitated and non-rehabilitated koalas from the burnt landscape used burnt habitat extensively (Fig. 2). The average nightly distance moved by each koala ranged from 74 to 448 m (Additional file 1), although 14 koalas moved more than 1 km in a night at least once during the study. There was no difference in the mean nightly distances moved by koalas between the three groups ($F_{2, 26} = 1.35$, $p = 0.28$; Fig. 3a). However, male koalas moved farther each night than females ($F_{1, 26} = 24.35$, $p < 0.001$), especially during spring ($F_{1, 24} = 33.03$, $p < 0.001$) and summer ($F_{1, 17} = 34.21$, $p < 0.001$; Fig. 4).

The maximum distance from the release location varied between koalas (405 m to 8,362 m for koalas included in statistical analyses; Additional file 1). Similarly, the displacement distance between the first and last locations recorded for each included koala varied, ranging from 32 to 6,567 m. For koalas tracked more than 50 days, both displacement distance, and greatest distance moved differed significantly between koala groups ($F_{2, 19} = 4.93$, $p = 0.019$; $F_{2, 19} = 5.94$, $p = 0.010$, respectively; Fig. 3b and c). On average, rehabilitated koalas had a displacement distance over three times that of non-rehabilitated koalas in both the burnt ($t(19) = 2.345$, $p = 0.03$) and unburnt landscapes ($t(19) = 2.615$, $p = 0.017$; Fig. 3b). We found a similar pattern for the greatest distance moved. The greatest distance moved was 2.5 times higher in rehabilitated koalas compared to non-rehabilitated in the burnt area ($t(19) = 2.240$, $p = 0.037$) and was three times higher compared to non-rehabilitated in the unburnt ($t(19) = 3.032$, $p = 0.007$; Fig. 3c). Displacement distance and greatest distance moved did not significantly differ between males and females ($F_{1, 19} = 0.295$, $p = 0.594$; $F_{2, 19} = 0.392$, $p = 0.539$, respectively).

We determined home-range sizes for 26 koalas (8 rehabilitated koalas, 8 non-rehabilitated koalas in the burnt landscape, 8 non-rehabilitated koalas in the unburnt landscape and for the two koalas that moved from unburnt area into burnt (Additional file 1). For the six koalas that did not reach an asymptote, five were tracked for less than 50 days (one rehabilitated, one

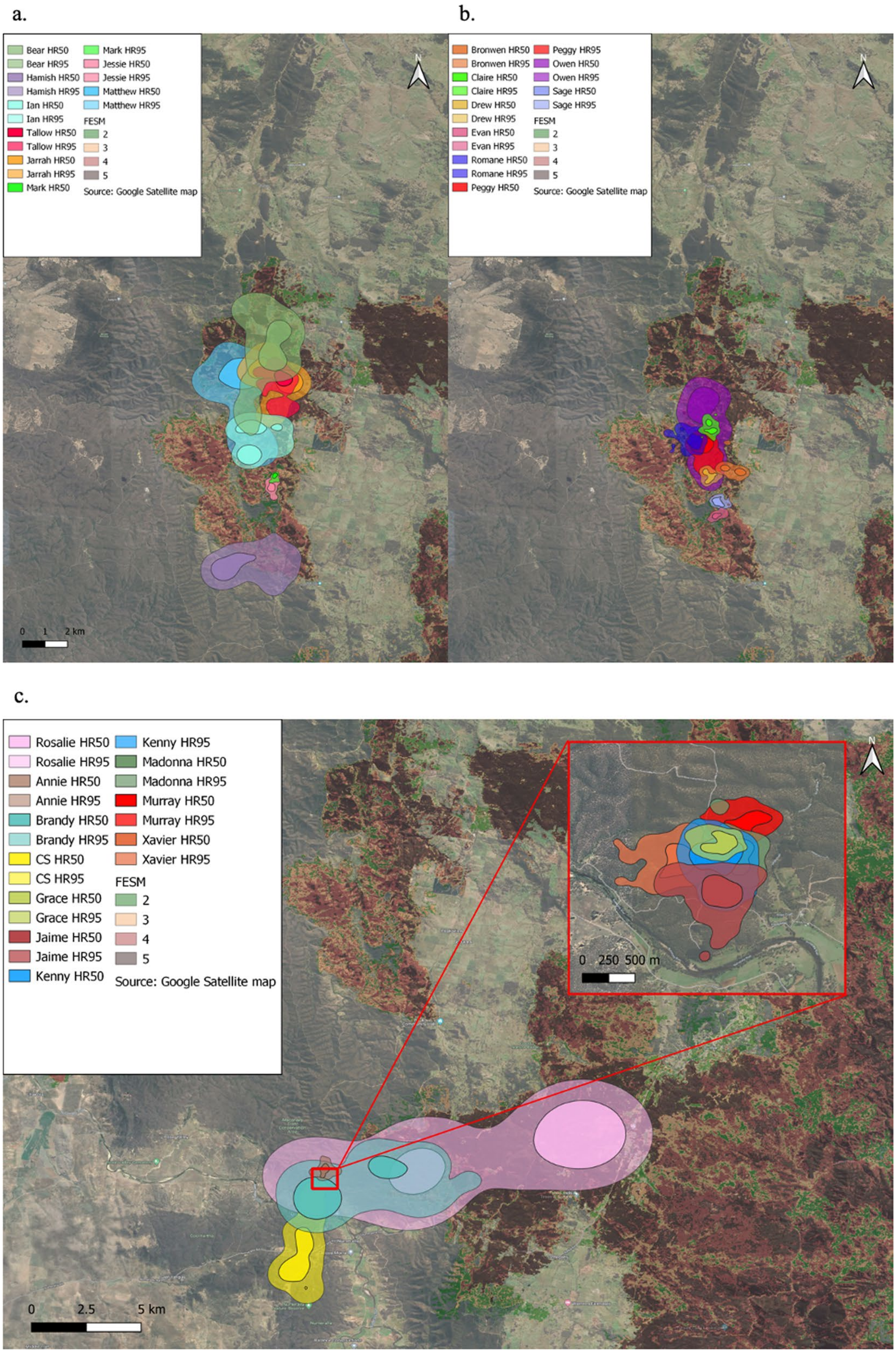

Fig. 2 Home ranges at KUD 50% (darker colours) and 95% (lighter colours) for rehabilitated koalas (**a**), non-rehabilitated koalas in burnt habitat (**b**) and non-rehabilitated koalas in unburnt habitat (**c**) (map data ©Google). Part c also shows two koalas that moved from unburnt into burnt habitat (Brandy and Rosalie). The inset on Fig. 2c shows the home ranges of six koalas in the unburnt area with comparatively smaller home ranges. Note that the scale on Fig. 2c differs from that of 2a and b

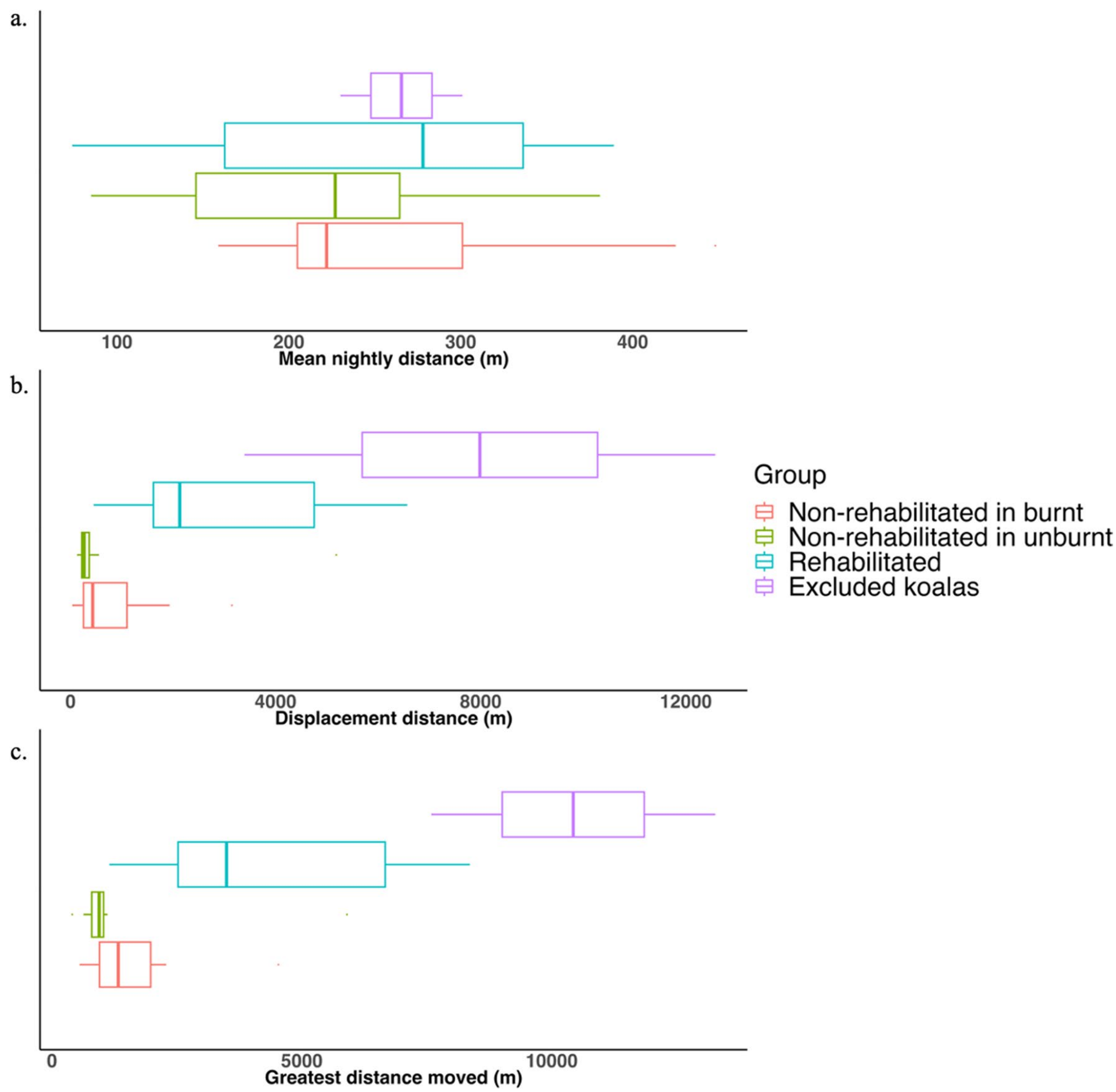

Fig. 3 Mean nightly distance moved by all koalas (n = 30) (**a**), displacement distance for koalas tracked > 50 days (n = 23) (**b**), and greatest distance moved from release point for koalas tracked > 50 days (**c**) in each study group. Excluded non-rehabilitated koalas (n = 2) moved from unburnt habitat into burnt habitat, and therefore did not fit the criteria for any group. Note that the lines within each bar are the median value

non-rehabilitated in the burnt, and three non-rehabilitated in the unburnt). The sixth koala was tracked for 120 days (a rehabilitated female), but she moved consistently in one direction. Home range size for the other 24 koalas in the treatment groups (11 females and 13 males) varied from 4.8 to 279.8 hectares at 50% KUD and 18.5 to 1,543.1 hectares at 95% KUD (Fig. 2; Additional file 1). At 95% KUD, mean home range was significantly different between koala groups ($F_{2, 20} = 3.639$, $p = 0.045$), with post-hoc analyses showing larger home range sizes for rehabilitated koalas compared to non-rehabilitated individuals in the unburnt landscape (t(20) = 2.291, $p = 0.033$; Table 1). 50% KUD, koalas in the rehabilitated group tended to have larger home ranges than koalas in the non-rehabilitated groups ($F_{2, 20} = 3.041$, $p = 0.070$; Table 1). On average, home range sizes for males and females were not significantly different at both 50% KUD ($F_{1, 20} = 0.121$, $p = 0.732$) and 95% KUD ($F_{1, 20} = 0.114$, $p = 0.739$), with large variation between individuals of both sexes. There was no group by sex interaction observed at either 50% or 95% KUD.

There was substantial overlap in the home ranges of tracked koalas at the 95% KUD, particularly in the unburnt area, but less so at the 50% KUD. For koalas living in the burnt landscape (n = 16), the core home range (50% KUD) of seven koalas did not overlap with any

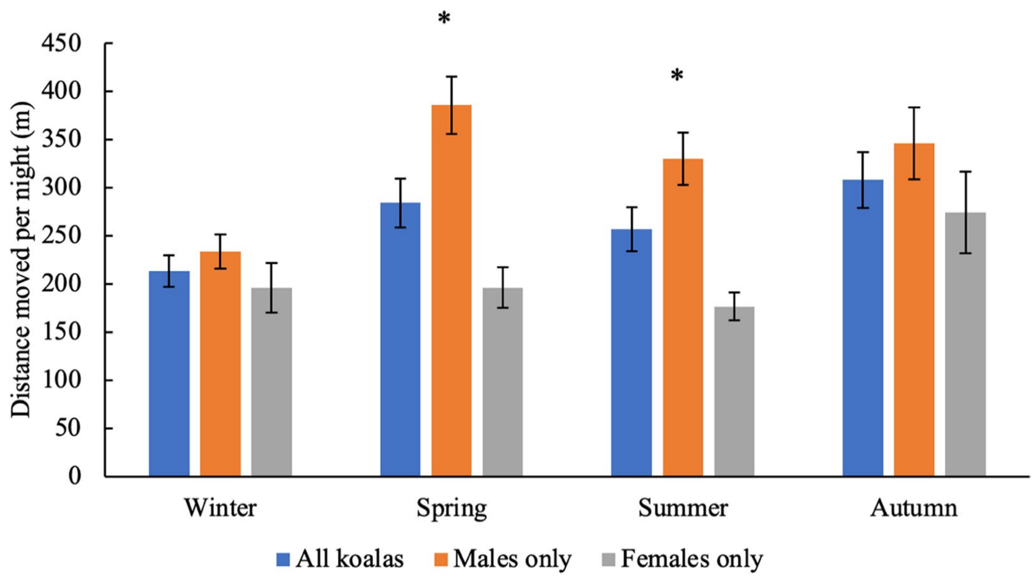

Fig. 4 Mean ± SE nightly distances moved by koalas during different seasons. Seasons with an asterisk above them indicate that the distances moved are significantly different ($p < 0.05$) between males and females

Table 1 Mean ± SE home range size at 50% and 95% kernel utilisation distribution (KUD) for koala groups and excluded non-rehabilitated koalas that used both habitat types

Group	50% KUD (ha)	95% KUD (ha)
Rehabilitated koalas (n = 8)	151.5 ± 39.8	773.8 ± 206.5
Non-rehabilitated in burnt habitat (n = 8)	58.0 ± 28.0	250.8 ± 123.3
Non-rehabilitated in unburnt habitat (n = 8)	45.1 ± 33.6	194.7 ± 142.7
Excluded koalas (n = 2)	1178.1 ± 598.8	5880.4 ± 2741.7

other tracked individuals. However, for the remaining nine koalas, overlap occurred with at least one individual and up to a maximum of three individuals. For koalas in the unburnt landscape, only one individual had a core home range that did not overlap with any other koalas. There was more extensive overlap for the remaining nine koalas in the unburnt landscape, with overlap observed with at least one other individual, and maximum overlap occurring with eight other tracked individuals.

Relative to their availability, koalas showed a preference for low and moderately burnt habitat over all other severity classes, including unburnt ($\lambda = 0.228$, $p = 0.002$) (Table 2). They also used habitat in the high fire severity class more often relative to its availability than the extreme or unburnt classes (Table 2). Fire severity classes were ranked in the following order of preference: low severity (class 2), moderate severity (3), high severity (4), extreme severity (5) and unburnt (0).

Discussion

Understanding how environmental disturbances such as wildfire affect animal movements and home ranges is important for assessing and guiding the conservation

Table 2 Relative preference for fire severity categories by koalas considering availability. A description of the categories is provided as per [131]. Symbols indicate whether koalas demonstrated a slight (+) or strong preference (+++) for, or avoidance (- or --) of different fire severities

	Severity class	Description	0	2	3	4	5
0	Unburnt	0% canopy and understorey burnt	0	---	---	---	-
2	Low	> 10% burnt understorey > 90% green canopy		0	+	+ + +	+ + +
3	Moderate	20–90% canopy scorch			0	+ + +	+ + +
4	High	> 90% canopy scorched < 50% canopy biomass consumed				0	+ + +
5	Extreme	> 50% canopy biomass consumed					0

and management of endangered species. In our study, the use of "control" groups within an experimental framework was particularly valuable because it allowed us to compare movement distances and home range sizes of rehabilitated and non-rehabilitated koalas in burnt and unburnt eucalypt woodland to understand how both bushfire and rehabilitation influenced movement behaviour. Our key findings were that: 1) contrary to expectations, the movements and home ranges of non-rehabilitated koalas were similar in burnt and unburnt habitat, and 2) as anticipated, displacement distances (distance between release and recapture points), the farthest distance moved from the release point, and home ranges were largest on average in rehabilitated koalas compared to their non-rehabilitated counterparts. Interestingly, our compositional analysis of habitat use showed that koalas preferred low to moderate burn severity, relative to all other burn severity categories. These findings have important implications for our current understanding of the value of burnt habitat for koalas and other marsupial folivores, and for refining intervention and release guidelines for koalas that are rescued from fire-affected areas.

Effects of fire on home ranges and movement

Our predictions of larger home ranges and longer movements in burnt habitat were based on the idea that fire reduces habitat quality (e.g. less food available; [87]) and competitive pressure from conspecifics due to fire-related mortality [27], forcing individuals to travel greater distances to find adequate food and/or allowing them to expand into unoccupied habitat immediately after a fire event. Unquestionably, leaf biomass, and therefore food availability, is substantially reduced in eucalypt forests after high severity fire [111]. Likewise, moderate to severe wildfire can substantially reduce koala abundance in burnt compared to unburnt areas [26, 71, 107]. Despite these changes, movement distances and home range sizes of non-rehabilitated koalas in burnt habitat were similar to those in unburnt habitat within our study timeframe, which spanned five to sixteen months post fire.

By the time our study commenced, food availability may not have been limiting for the remaining animals. Eucalypts are well-adapted to fire, and many species produce new growth from epicormic buds within days or weeks [16, 106]. In addition, a reduction in the availability of canopy foliage may be offset by an increase in the nutritional quality of epicormic leaves in a relatively short time after fire. This is further supported by our compositional analysis of habitat use, which demonstrated that koalas showed a preference for low to high burn severity over unburnt habitat, which could be linked to the epicormic foliage in these areas being more nutritious. Recent studies have shown that epicormic leaves are higher in nutritional quality in some eucalypt species than the adult-phase leaves that are present in unburnt areas [65]. This may have contributed to our findings, since many trees in the burnt landscape had at least some epicormic growth at the time we initiated our study.

It was interesting to note that two koalas in our study who were initially captured as part of the group in unburnt habitat moved into burnt areas. Although they were excluded from statistical analyses, this behaviour is worth discussing. At a minimum, the movement from unburnt to burnt habitat reinforces the idea that burnt landscapes can provide habitat for koalas. Additionally, the compositional analysis showed that koalas preferred low, moderate and highly burnt areas over extremely burnt areas and even unburnt areas, demonstrating that burnt areas can support koalas, and may even be favoured if the canopy has not been completely consumed. Other studies have observed similar results, with some grazing and browsing mammals attracted to burnt areas for the new growth of plants recovering from fire [4, 5, 63, 92]. The movement of individuals from unburnt to burnt areas should also be considered in the context of post-fire recovery, whereby populations in unburnt areas can drive the recolonisation of burnt habitat [128, 143]. It would be valuable to design future studies to investigate the emigration of koalas from unburnt to burnt habitat to better understand how this may contribute to population recovery after wildfire.

Effects of rehabilitation on home ranges and movement

Rescuing and rehabilitating wildlife can be stressful for animals [139], and the risks to animal welfare need to be weighed against the potential benefits for both the individual and the population [24]. Some species have a low survival rate after release following rehabilitation [11], while other species reintegrate back into the wild with minimal expense to fitness [95]. The effects of rehabilitation and release can be complex, with various factors contributing to outcomes [74, 93]. We found that rehabilitated koalas had larger home ranges and larger displacement distances from their release site than non-rehabilitated koalas in both the burnt and unburnt landscape. While several studies have looked at koala movements following release from rehabilitation (e.g., [40, 48, 74, 88]), only Matthews et al. [88] also compared their findings to non-rehabilitated koalas in the same area. In contrast to us, they found that rehabilitated koalas in Port Stephens had similar home range sizes to non-rehabilitated koalas. Future research is needed to better understand which factors drive these differences and could provide insights into when koalas will reintegrate most easily into their habitat after rehabilitation.

The larger movements of rehabilitated koalas are unlikely to be due to their release into burnt habitat per se, because their movements differed from non-rehabilitated koalas in the same area. Previous studies have found that rehabilitated koalas that are released away from their capture location often disperse to other areas [9, 74]. However, this does not explain our findings either because koalas in all groups were released at the location from which they were captured. Instead, there are other possible explanations, such as larger movements to refamiliarise themselves with the landscape, or competitive exclusion by established, non-rehabilitated koalas. For example, rehabilitated red foxes (*Vulpes vulpes*) had larger home ranges and travelled farther from their release site than wild individuals, which was attributed to captivity causing territorial displacement [135]. To address this, future research could look at interactions among rehabilitated and non-rehabilitated koalas in the same landscape to better understand their social dynamics, particularly when male–female and male-male interactions are likely to be high, such as during the breeding season [142]. This could guide more effective management of rescued koalas and aid rehabilitation and release practices.

Despite the greater distance moved and larger area used by rehabilitated individuals, measured health parameters were similar between koalas in all groups throughout the study [64]. Furthermore, there was no change in the chlamydia status of individuals (a disease which can be triggered by stress; [145]), and koalas in all groups improved in body condition over the study timeframe and had high rates of survival [64]. This suggests that any costs associated with moving away from release locations did not have substantial longer-term (i.e. at nine months post-release) effects on the health of individuals. In combination with our findings, there is strong evidence from multiple studies that rehabilitated koalas are capable of integrating back into the landscape, including when it is burnt, and they can successfully form home ranges, although they may initially need to move farther from their release site to re-establish their territory [48, 74, 88].

Based on our findings, koalas in fire-affected landscapes that are injured or in poor body condition should be taken into care, but otherwise, uninjured koalas should be allowed to remain in burnt landscapes, as long as some browse is available. For animals that are taken into care, our study demonstrates that rehabilitated individuals can be safely released at their rescue location rather than moving them to areas that are less disturbed, a practice that is sometimes undertaken [74]. Our findings should give wildlife carers confidence that rehabilitated koalas can be successfully released into burnt habitat, and to incorporate this practice into release policy. More research like this is needed across the range of the koala, since tree species composition can have substantial effects on food quality for koalas before and after fire [65]. In addition, climatic conditions can vary considerably across the koala's large distribution and reduced canopy cover after fire may impact thermoregulation more substantially in some regions than others. The ability to develop region specific guidelines would assist policy-makers, landscape managers and the wildlife care sector to more effectively conserve koalas and their habitat in the face of increasingly severe and frequent fires from anthropogenic climate change [116].

Challenges of interpreting animal movements

Studying animal movements and interpreting the outcomes of home range analyses can be challenging, as many animal species do not use their home range, or move, in a uniform way [52]. It is often assumed that animal movement data captured at a particular time adequately reflects normal behaviour, however it fails to recognise dispersal and shifts in habitat use due to changes in the landscape and environmental conditions [108]. Core home range measurements (i.e., 50% KUD in our study) focus on where animals spend the majority of their time, and they remove longer and more directional movements that are considered for the 95% KUD. We observed that many of the rehabilitated koalas gradually moved away from their release sites until they remained in one area more consistently. These gradual directional movements were captured in the 95% KUD, whereas the 50% KUD was more concentrated around the area where koalas completed the study (see Fig. 2).

Similar to some of the koalas in our study, Ream et al. [115] observed a lone female wolf dispersing a large distance and then settling into a well-defined home range, and intensively using two core areas. Spencer [130] suggested that the reason for this type of behaviour may simply be exploration that resulted in finding a good place to stay and settle down. While our KUD analyses represent the area used by koalas over the study period, the movements of some koalas (e.g. moving from unburnt to burnt habitat or dispersing after release from rehabilitation) may not be typical of home range use and extent at other times. Researchers should be mindful of these issues when interpreting the output from home range analyses [43, 67, 151]. In addition, end users, such as policy makers and conservation practitioners, need to use caution when translating this type of output into management recommendations. For example, there may be limited value in using "home range" size from rehabilitated koalas to understand the typical amount of area needed to support koalas in the Monaro region.

Our study, like many tracking studies, was restricted in scope by the logistical limitations of tracking many different individual animals across rugged terrain [123]. However, a larger number in each group would have provided more statistical power, particularly given the large variation between koalas in core home range sizes in our study area (5 ha to 280 ha). The "trend" observed in 50% KUD between rehabilitated and non-rehabilitated koalas ($p = 0.07$) may have been significant with additional data. Notably, the variation that we observed between individual koala home ranges is not unusual and similar variability has been reported in other koala tracking studies [6, 39, 41, 69, 85, 88]. This demonstrates that, in any study, there is a need to consider how large variations in movement behaviour between animals might influence the capacity to address project aims when selecting the number of individuals to monitor.

Other findings

Other studies have found that movement parameters differ between males and females [30, 88, 120]. We found that male koalas moved farther each night on average than females, particularly during spring and summer. This is likely because spring and summer are the breeding season for koalas [70]. Male koalas also often have larger home ranges than females [41, 66, 88, 148] and tend to disperse farther [28]. In our study, home range sizes were similar between the sexes, and the longest movements or dispersals away from the release site were undertaken by females. This demonstrates that variability in movements is not explained by sex alone, but also by differences between individuals.

The home ranges observed in this population were generally larger than other studied koala populations. Other studies in NSW have reported home range sizes ranging from 4.9 to 58.9 ha using the fixed kernel method (FK) at 95% [48, 61, 66, 88], which is considerably smaller than the 95% KUD reported for the non-rehabilitated koalas in our study (250.8 hectares in the burnt and 194.7 hectares in the unburnt). Some studies in Queensland, however, have reported larger home ranges, including up to 135 ha in Blair Athol [39]. It is important to acknowledge that home range size estimates will vary depending on the method or technique used. Kernel methods are used to calculate utilisation distributions (i.e. distribution of an animal's position) by smoothing locational data and creating a density estimate [137, 152], and are thought to be more accurate measures compared to minimum convex polygons (MCPs) and the harmonic mean [36, 151, 153]. MCPs are thought to either under- or over-estimate home range size, depending on sample size [36] and over-estimates have also been documented for the harmonic mean [96]. For example, Goldingay and Dobner [48] found larger home ranges when using MCPs (e.g., average of 37.4 ha compared to the 8 ha at FK 95%). Despite this, it is likely that the larger home ranges and movement distances in our study are not just an artefact of using different home range methodologies, but demonstrate that some koalas in the NSW Monaro use larger areas than koalas that have been studied elsewhere.

There are a number of reasons why home range sizes differ between populations in other mammal species. These include differences in the availability of resources [126], disturbance [101], environmental conditions (such as rainfall; [28]) and population densities [46, 124], with populations at lower density having larger home ranges than areas with higher densities [10]. Several of these factors likely contribute to the larger home ranges of koalas recorded in our study. For example, the Snowy Monaro region has a relatively low density koala population compared to some other areas, with Cristescu et al. [26] estimating 0.032 koalas per hectare in burnt habitat at Peak View, NSW and 0.041 koalas per hectare in unburnt habitat in Numeralla, NSW. Higher density populations in other parts of NSW are typically around 0.3 koalas per hectare [68], and can be much higher in other states (e.g., 10.1–18.4 koalas per hectare recorded in Cape Otway, Victoria between 2011 and 2013; [147]). The quality of food resources may be lower or more dispersed in our study area compared to other areas [132]. However, this region is one of the few areas in Australia where koala populations appear to be stable rather than declining [3]. Our study provides the first information about the movements and home ranges of this understudied population of koalas, which will assist with the development of local management plans.

Conclusions

Studies such as this one that document the movement ecology of species after fire play an important role in understanding the ecological implications of wildfire, and can help guide conservation efforts by evaluating how burnt landscapes are used. Incorporating an experimental design with "treatment" and "control" groups in the same study can help identify disturbance effects on animal movements and landscape use with more certainty than comparing data collected from different areas, with different populations and/or at different times. Our findings fill important knowledge gaps about post-rehabilitation release success and the value of burnt habitat to rehabilitated and non-rehabilitated animals, and can assist with decisions about the rescue and release of wildlife in burnt landscapes.

Encouragingly, despite the catastrophic wildfires of 2019–2020, our study found that burnt woodlands in the Monaro region of the NSW Southern Tablelands provided adequate resources for koalas to persist and recover, which is further supported by the high body condition of all koalas at the end of the study [64]. In addition, apart from habitat that burnt in the extreme category, koalas spent proportionally more time in burnt than unburnt areas within their home ranges. The relatively mild conditions and higher than average rainfall from multiple years of La Niña after the fires also may have contributed positively to landscape and wildlife recovery. With wildfires predicted to increase in frequency and severity worldwide in response to climate change [60], the success of wildlife management and conservation efforts will likely depend on improving our understanding of the ecological impacts of fire on species and their habitats [122].

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40462-024-00519-0.

Additional file1 (DOCX 24 KB)

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Availability of data and materials
All data available at: https://datacommons.anu.edu.au/DataCommons/

Declarations

Ethics approval
This research was approved by the NSW Government Department of Planning, Industry and Environment Animal Ethics Committee (permit number 200421/04) and was conducted in accordance with the Australian Code for the care and use of animals for scientific purposes.

Competing interests
The authors declare no competing interests.

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