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Non-preferred habitat increases the activity area of the endangered northern quoll (*Dasyurus hallucatus*) in a semi-arid landscape

Cowan, M. A.; Moore, H. A.; Hradsky, B. A.; Jolly, C. J.; Dunlop, J. A.; Wysong, M. L.; Hernandez-Santin, L.; Davis, R. A.; Fisher, D. O.; Michael, D. R.; Turner, J. M.; Gibson, L. A.; Knuckey, C. G.; Henderson, M.; Nimmo, D. G.

Published in:
Australian Mammalogy

DOI:
[10.1071/AM22006](https://doi.org/10.1071/AM22006)

E-pub ahead of print: 28/09/2022

Document Version
Peer reviewed version

[Link to publication on the UWS Academic Portal](#)

Citation for published version (APA):

Cowan, M. A., Moore, H. A., Hradsky, B. A., Jolly, C. J., Dunlop, J. A., Wysong, M. L., Hernandez-Santin, L., Davis, R. A., Fisher, D. O., Michael, D. R., Turner, J. M., Gibson, L. A., Knuckey, C. G., Henderson, M., & Nimmo, D. G. (2022). Non-preferred habitat increases the activity area of the endangered northern quoll (*Dasyurus hallucatus*) in a semi-arid landscape. *Australian Mammalogy*. <https://doi.org/10.1071/AM22006>

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1 **Non-preferred habitat increases the activity area of the endangered**
2 **northern quoll (*Dasyurus hallucatus*) in a semi-arid landscape**

3
4 **Running header: Northern quoll habitat selection**

5
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32
33 **Key words:** GPS, habitat use, activity area, mesopredator, movement ecology, northern quoll,
34 *Dasyurus hallucatus*, riverbed, rocky habitat, spinifex sandplain

36 **Abstract**

37 Animal conservation requires a sound understanding of the movement ecology and habitat
38 selection of the species in question. A key component of this is identifying habitats that animals
39 actively seek or avoid. We quantified habitat selection and investigated the drivers of
40 variability in the short-term activity area of a small, endangered mesopredator, the northern
41 quoll (*Dasyurus hallucatus*), in the Pilbara region of Western Australia. We collated,
42 standardised, and analysed 14 northern quoll GPS tracking events from four studies conducted
43 between 2014 and 2018. Northern quolls selected activity areas in locations that were more
44 topographically rugged than the broader landscape, characterised by higher percentage cover
45 of rocky habitat and riverbed, and lower percentage cover of spinifex sandplain. The size of
46 their activity area also increased with higher percentage cover of non-preferred spinifex
47 sandplain. Therefore, the destruction of habitats preferred by northern quolls—such as mining
48 of rocky habitat—and introduction of structurally simple habitat like spinifex sandplain, is
49 likely to negatively impact resource availability and lead to altered movement patterns that
50 could decrease survival. Future conservation planning should place emphasis on the protection
51 of rugged rocky habitat for northern quolls, as well as efficient movement pathways between
52 patches of this critical habitat.

53 **Introduction**

54 Effective conservation requires knowledge of the spatial and temporal use of preferred habitats
55 by target species (Dellinger *et al.* 2020). Animal space use reflects resource availability in the
56 landscape (Michel *et al.* 2020; Wysong *et al.* 2020). If landscapes are resource-rich, animals
57 travel shorter distances (Doherty *et al.* 2019; Martin and Martin 2007; Viana *et al.* 2018).
58 Conversely, where resources are limited, animals travel further to access food, shelter, or mates
59 (Gardiner *et al.* 2019; Rus *et al.* 2020; Stobo-Wilson *et al.* 2021). In fragmented landscapes,
60 where an animal's preferred habitat is interspersed among non-preferred habitat, animals may
61 need to acquire resources from multiple patches of the preferred habitat type (Dunning *et al.*
62 1992). The spatial extent and configuration of non-preferred habitat can affect the capacity of
63 animals to move between preferred habitat (Nimmo *et al.* 2019): large areas of non-preferred
64 habitat can lead to increased travel time (Beasley and Rhodes 2010), reducing foraging
65 efficiency while increasing predation risk and energy expenditure (Brown 1988; Haapakoski
66 *et al.* 2013). These behaviours are often influenced by predator interactions and the 'landscape
67 of fear', where animals perceive certain habitats as riskier than others (Bleicher 2017; Brown
68 1988).

69
70 One species which lacks information about its movement and habitat use is the northern quoll
71 (*Dasyurus hallucatus*)—an endangered, nocturnal mesopredator native to northern Australia
72 (Moore *et al.* 2019). Over the past century, northern quolls have suffered substantial range
73 declines (Braithwaite and Griffiths 1994; Moore *et al.* 2019), presumably due to habitat loss,
74 introduced predators (namely the feral cat, *Felis catus*), altered fire regimes, and cane toads
75 (*Rhinella marina*) (Ibbett *et al.* 2018; Moore *et al.* 2019; Woinarski *et al.* 2010). The Pilbara
76 region of Western Australia contains the last cane toad-free populations of northern quolls
77 (Moore *et al.* 2019; Woinarski *et al.* 2014). Yet quolls in the Pilbara are far from secure (Cramer
78 *et al.* 2016; Moore *et al.* 2021a). Drill and blast mining operations often target the rocky habitat
79 that also provides crucial denning sites for northern quolls (Ramanaidou and Morris 2010),
80 because of their rich deposits of minerals such as iron ore, resulting in a structurally simplified
81 landscape (Cramer *et al.* 2016; Henderson 2015). Based on previous research, we know
82 northern quolls are most likely to be found in rugged rocky outcrops but are less common in
83 spinifex sandplain habitats (Hernandez-Santin *et al.* 2016; Moore *et al.* 2021b).

84

85 While this research has informed much conservation work (Moore *et al.* 2021a), we know very
86 little about how rocky habitat and spinifex sandplain influence northern quoll movement and
87 space use, and even less about how northern quolls interact with other habitat types (Cramer *et*
88 *al.* 2016). Understanding how northern quolls use different habitats, and how these habitats
89 influence their movements, will allow greater protection of critical habitat and better inform
90 rehabilitation projects which seek to reconnect remnant habitat or replicate northern quoll
91 habitat that has been disturbed or destroyed (e.g., Cowan *et al.* 2020b).

92

93 In this study, we investigate the movement ecology of northern quolls in a naturally fragmented
94 landscape of rocky outcrops, spinifex sandplains, *Acacia* stands, and dry riverbeds in the
95 Pilbara, Western Australia. Riverbed in the Pilbara is often associated with rocky habitat, while
96 *Acacia* stands are patchily distributed amongst spinifex sandplain and rocky habitat (Van
97 Vreeswyk *et al.* 2004). Previous estimates of northern quoll movement are mostly derived from
98 Very High Frequency (VHF) tracking (e.g., Cook 2010; King 1989; Oakwood 2002)—a
99 technology now largely superseded by Global Positioning System (GPS) tracking (e.g.,
100 Heiniger *et al.* 2020; Hernandez-Santin *et al.* 2020). We collated, standardised, and analysed
101 GPS data from four studies to investigate habitat selection, and the influence of habitat type on
102 movement, by northern quolls. We developed two predictions based on existing knowledge of
103 northern quoll behaviour and ecology:

104

105 First, we predicted that northern quolls would select for habitats which are topographically
106 rugged, such as rocky habitat and riverbed—which likely offer many resources required for
107 survival. The landscape of fear also suggests that quolls would avoid simpler habitats like
108 spinifex sandplain and *Acacia* stands. Rocky habitat is likely seen as safer by northern quolls,
109 as feral cats, an agent of northern quoll decline—and a threat to other quoll species (Fancourt
110 *et al.* 2015)—are more common and superior hunters in simpler habitats like spinifex sandplain
111 (McGregor *et al.* 2015).

112

113 Second, we predicted that northern quoll activity areas (i.e., the movement footprint of northern
114 quolls over seven nights) would be larger when containing higher percentages of presumably
115 non-preferred habitat, such as spinifex sandplain, due to a lack of necessary resources for
116 quolls, requiring them to travel further to access preferred habitat (e.g., rocky habitat).

117 **Materials and methods**

118 **Study area**

119 The Pilbara bioregion covers 179,000 km² of Western Australia and experiences a semi-arid
120 climate, with average maximum temperatures of 37°C during summer and 25°C during winter
121 (McKenzie *et al.* 2009). Annual rainfall is variable (250–500 mm), and falls predominately
122 between December and February (Bureau of Meteorology 2020). The Pilbara is characterised
123 by patches of rocky habitat with rugged hills, deep gorges, rough escarpments, and sandy plains
124 (Carwardine *et al.* 2014; Van Vreeswyk *et al.* 2004). The flora is diverse but is predominately
125 composed of *Acacia*, *Triodia* (spinifex), and *Eucalyptus* species, the composition of which is
126 largely influenced by local geology and fire history (Maslin and van Leeuwen 2008; Van
127 Vreeswyk *et al.* 2004).

128
129 We studied habitat selection of northern quolls at four sites in the Pilbara, using data from four
130 different studies conducted between 2014 and 2018 (Biologic 2016; Cowan *et al.* 2020b;
131 Hernandez-Santin *et al.* 2020; Moore, unpubl. data; Figure 1; Table S1 & S2). Studies occurred
132 primarily on Karriyarra, Ngarluma, and Nyamal country, and occupied a mixture of pastoral
133 leases, national parks, and mining tenements (Table S1). Study sites were broadly similar in
134 that they all contained rocky habitat, spinifex sandplain, and scattered *Acacia* stands. One site,
135 Red Rock, also contained a sandy riverbed which flows seasonally and is closely associated
136 with rock (Van Vreeswyk *et al.* 2004; Figure 2).

137

138 **Maps of habitat features**

139 We used QGIS v3.12 (QGIS Development Team 2020) to create a map of habitat features for
140 each site. We applied semi-supervised classification of normalised difference vegetation index
141 (NDVI) layers (Pandey and Kulhari 2018), derived from Sentinel-2 imagery (USGS 2020), to
142 map the six habitat types we considered likely to influence the spatial ecology of northern
143 quolls: rocky habitat, spinifex sandplain, *Acacia* midstory over spinifex understory (henceforth
144 *Acacia* stands), sandy dry riverbeds (henceforth riverbed), water, and disturbed ground (e.g., a
145 road or cleared land). Feature layers for the habitat maps were captured at a scale of 10 m for
146 each site during the year tracking took place—except for at Red Rock where we used a
147 consistent layer (2014) for each year. Red Rock had no fires between 2014 and 2018 and habitat
148 features remained relatively consistent across years. Habitat feature maps were cross-examined
149 with the corresponding satellite imagery to ensure the accuracy of habitat feature classification

150 (as per Tilahun and Teferie 2015). During analysis, we did not investigate northern quoll
151 selection of water or disturbed ground due to a lack of representation among sites.

152

153 **Animal capture and data acquisition**

154 Trapping effort varied slightly between the studies, however, the same broad method was
155 applied, and all live animal research was approved by the respective institutional animal ethics
156 committees (see Acknowledgements). Wire cage traps (45 cm × 17 cm × 17 cm, Sheffield Wire
157 Co., Welshpool, WA) were deployed in transects during autumn, winter, or spring between
158 2014 and 2018 (see Biologic 2016; Cowan *et al.* 2020b; Hernandez-Santin *et al.* 2019).
159 Trapping did not occur during summer to avoid trapping females raising young during this time
160 (Dunlop *et al.* 2014). Traps were placed in rocky and riparian habitats because these are the
161 areas in which northern quolls locate their dens in the Pilbara (Hernandez-Santin *et al.* 2022),
162 resulting in an increased likelihood of trap success. Traps were baited with universal bait (oats
163 and peanut butter) or a mixture of the universal bait and sardines (as per Dunlop *et al.* 2014).
164 Traps were opened in the evening and checked the following morning. All individuals were
165 processed at the site of trapping, which involved taking a series of morphological
166 measurements, recording sex and weight, and attaching a GPS unit (provided the unit did not
167 exceed five percent of the animal's bodyweight). GPS units were deployed on 25 individuals
168 for up to 37 days before animals were re-trapped and the GPS unit was removed. GPS units
169 were fitted as collars or backpacks; brands and tracking methods differed slightly between
170 studies due to limitations of battery life, data storage, and study time (Table S2).

171

172 **Data screening and processing**

173 To eliminate errors and reduce bias due to variation in study methods, data were screened prior
174 to being included in analysis. Data contributed by Biologic (2016) had been pre-screened by
175 the authors to discard all locations not recording elevation, as well as those with low GPS
176 accuracy (horizontal dilution of precision greater than 5). We screened all datasets further by
177 discarding GPS points before 12:00 pm on the day of collaring, as well as all those after 12:00
178 pm on the date before collar retrieval, as GPS fixes may have been affected by quolls being in
179 a trap. Unrealistic GPS fixes were removed based on the average sprinting speed of northern
180 quolls (4.5 m s⁻¹) (Wynn *et al.* 2015), where points too far to be reached in the time between
181 fixes were excluded (Bjørneraas *et al.* 2010).

182

183 To ensure that GPS locations reflected the times when northern quolls were active, we only
184 included GPS locations recorded between 6:00 pm and 6:00 am. Individuals with fewer than
185 30 fixes, as well as individuals whose GPS units failed within the first day, were removed
186 because there was unlikely sufficient data to accurately measure activity areas (Girard *et al.*
187 2002; Seaman *et al.* 1999). We did not standardise fix rates among datasets because doing so
188 resulted in many unusable individuals with too few GPS locations, and differences in fix rate
189 are often negligible when applying kernel density estimation (Huck *et al.* 2008; Mitchell *et al.*
190 2019; Peris *et al.* 2020).

191

192 **Activity area size**

193 Many tracking events did not represent complete home ranges of each individual and instead
194 represented a sample of each individual's home range. This is because they did not reach an
195 asymptote with fixes added sequentially (i.e., over time) at 10-fix intervals. An asymptote is
196 calculated by plotting activity area with the number of fixes—with 10 sequential fixes added
197 in each iteration in this case—and is reached when adding additional fixes has little to no effect
198 on the size of the activity area, thus representing a true home range (Harris *et al.* 1990). Instead,
199 to account for differing tracking durations among individuals, we standardised each dataset to
200 a total period of seven nights (one week) and refer to the area used by northern quolls during
201 this time as their 'short-term activity area' (henceforth activity area) (Doherty *et al.* 2019).
202 Some individuals were tracked for one week, but GPS tracking ceased before seven nights of
203 data could be reached (likely due to battery failure or memory limitations). Therefore, six
204 individuals were tracked for less than seven nights, and six individuals were tracked for seven
205 nights ($n = 12$). The shorter tracking duration for these individuals is accounted for in further
206 analyses (see below). For one individual (E6CA67) tracked for 29 nights, we isolated each
207 seven-night period (hereafter referred to as a 'tracking event'), separated by a buffer of one
208 night between each. Each tracking event was treated as an individual event, and therefore the
209 individual quoll appears in the data three times. We accounted for this by including 'individual'
210 as a random effect in all analyses (Bates *et al.* 2015).

211

212 We estimated northern quoll activity area from utilisation distributions (UDs) at the 95%
213 isopleth using fixed kernel density estimation (KDE). Kernel density estimation uses a
214 smoothing parameter or bandwidth (h) to smooth GPS points, creating a probability density
215 estimate which reflects the intensity of use within an animal's activity area (Signer *et al.* 2015).
216 We used the *ad hoc* method ($h_{ad hoc}$) (referred to as 'reference scaled' in the R package; see

217 below) to determine h because $h_{ad hoc}$ is robust to sample size, accurately reflects the true
218 activity area, and is consistent and repeatable (Kie 2013). We used fixed KDE (where the kernel
219 width remains the same regardless of the distance between points) instead of adaptive KDE
220 (where the kernel width increases with increasing distance between points) because adaptive
221 KDE can sometimes over-estimate activity area size (Blundell *et al.* 2001; Kernohan *et al.*
222 2001; Powell 2000). We used the package “rhr” (Table S3, Signer and Balkenhol 2015) in R
223 version 1.3.959 to estimate activity area (R Core Team 2020).

224

225 **Habitat selection**

226 To analyse northern quoll habitat selection, we quantified the percentage of habitat types in
227 each “used” short-term activity area ($n = 14$) and 10 randomly placed circular “available”
228 activity areas per individual ($n = 140$), equal in size to the activity area of the individual being
229 measured and randomly placed within the available landscape (Squires *et al.* 2013; Wysong *et al.*
230 *et al.* 2020). Due to the fragmented nature of northern quoll habitat in the Pilbara (Moore *et al.*
231 2021b), available activity areas for each individual were sampled within habitat considered
232 accessible by that individual (Hazen *et al.* 2021). To define the boundaries for the available
233 landscape for each individual, we followed a similar method to Wysong *et al.* (2020). We fitted
234 a 100% minimum convex polygon (MCP) to the GPS data of each individual tracking event.
235 We then placed a buffer around each MCP equal to the radius of the largest northern quoll
236 activity area if assumed to be circular (897 m). We then subtracted the radius of the activity
237 area being measured. We used the “extract” function in the “raster” package to determine the
238 proportion cover of each habitat type within each “used” and “available” activity area in R
239 (Hijmans *et al.* 2015).

240

241 To test our predictions about selection and avoidance of the four habitat types, we used Beta-
242 Binomial Mixed Models (BBMMs) to evaluate if the proportion cover of each habitat type
243 differed between “used” and “available” activity areas. BBMMs allow for the analysis of
244 proportion data—including over-dispersed proportion data—and random effects (Douma and
245 Weedon 2019). We did not account for tracking duration in BBMMs because the data were
246 proportion data which was relative to each individual tracking event. A separate BBMM was
247 fitted for each habitat type. The response variable was the proportional cover of the habitat type
248 (rocky habitat, riverbed, spinifex sandplain, *Acacia* stands) within an activity area, and the
249 predictor variable was the “used” or “available” activity area. The reference category
250 (intercept) was the “available” activity area category. Selection (or avoidance) was evaluated

251 using a p -value statistical significance approach. We included ‘individual’ and ‘site’ as random
252 effects (Muff *et al.* 2020). BBMMs were fitted using the package “PROreg” in R (Najera-
253 Zuloaga *et al.* 2020).

254

255 We also investigated whether northern quolls selected for highly topographically rugged areas.
256 The topographic ruggedness index (TRI) is defined as the difference in elevation between a
257 cell and the eight cells surrounding it (Riley *et al.* 1999). To create topographic ruggedness
258 index maps for each site, we sourced Digital Elevation Models (30 m scale) (Gallant *et al.*
259 2009) , and used the “Terrain Ruggedness Index” function in QGIS (QGIS Development Team
260 2020). We overlaid the “used” and “available” northern quoll activity areas onto topographic
261 ruggedness maps and identified the median topographic ruggedness index for each activity
262 area. To evaluate if northern quolls used activity areas with a higher median topographic
263 ruggedness index compared to the broader landscape, we fitted a Generalised Linear Mixed
264 Model (GLMM) with ‘individual’ as a random effect, and median topographic ruggedness as
265 a continuous response variable (Bates *et al.* 2015). We could not include site as a random effect
266 due to small sample size. The categorical predictor variable was either the “used” or “available”
267 (intercept) activity area. GLMMs were fitted using the package “lmerTest” in R (Kuznetsova
268 *et al.* 2015).

269

270 **Determinants of activity area**

271 To test our prediction that northern quoll activity areas would increase in size with an
272 increasing percentage cover of spinifex sandplain, we developed Linear Mixed Models
273 (LMMs) in which the response variable was the “used” activity area size, and the predictor
274 variable was one of: median topographic ruggedness index (median TRI), sex, weight, or the
275 proportional cover of rocky habitat, spinifex sandplain, or riverbed. We included only
276 univariate models to simplify model selection and preclude overfitting, due to our small sample
277 size. We also only considered habitat variables that northern quolls either selected or avoided
278 disproportionately more than what was available in the broader landscape (i.e., rocky habitat,
279 spinifex sandplain, and riverbed), therefore, *Acacia* stands were excluded. The response
280 variable was \log_{10} transformed because predictor variables had non-linear relationships, and
281 ‘individual’ was included as a random effect to account for the repeat sampling of the same
282 individual (Bates 2010). We could not include ‘site’ as a random effect due to small sample
283 size (Bates *et al.* 2015; Stratmann *et al.* 2021). To account for some individuals having less
284 than seven nights of data, we included ‘nights’ as an offset in the model, which was the number

285 of nights each individual was tracked (Stobo-Wilson *et al.* 2021). This variable was also \log_{10}
286 transformed. GLMs were fitted using the package “lme4” in R (Bates *et al.* 2020).

287

288 We applied second order Akaike’s Information Criterion (AICc) ranking to determine the best
289 model explaining variation in activity area size. We determined the goodness of fit (r^2) for all
290 models and acknowledged models as having substantial support when Δ AICc < 2 (Burnham
291 and Anderson 2001; Mac Nally *et al.* 2018). We used the “AICcmodavg” package in R to
292 conduct model selection (Mazerolle and Mazerolle 2017).

293 **Results**

294 Of the 25 northern quolls collared in the four studies, data for eight female and four male
295 northern quolls met our study criteria ($n = 12$), resulting in 14 tracking events (Figure S1).
296 Three of these tracking events occurred during autumn, seven during winter, and four during
297 spring (Table S4). Nine tracking events occurred at Red Rock, three at Cattle Gorge, and one
298 each at De Grey Ridge and Python Pool. After data were trimmed to the relevant diel period,
299 five location errors were removed from the datasets of three northern quolls in total. The mean
300 number of GPS fixes for all weekly (seven-night) short-term activity areas was 267 ± 57 fixes
301 (mean \pm SE) while the minimum was 69 fixes, and the maximum was 418 fixes (Table 1; Table
302 S4).

303

304 **Activity area size**

305 For weekly short-term tracking events, the mean activity area for females and males combined
306 was 153.42 ± 38.69 ha (Table 1). The mean weekly activity area for females was 91.24 ± 24.39
307 ha (min = 22.96 ha, max = 128.62 ha), while the mean weekly activity area for males was
308 215.61 ± 61.75 ha (min = 53.84 ha, max = 340.54 ha) (Table 1; Table S4).

309

310 **Habitat selection**

311 Northern quolls selected activity areas in locations with significantly higher percentage cover
312 of rocky habitat and riverbed, and significantly lower percentage cover of spinifex sandplain,
313 compared to the available landscape (Figure 3, Table 2). Their activity areas had a similar
314 percentage of *Acacia* stands compared to the available landscape (Figure S2; Table 2). Finally,
315 northern quolls selected activity areas in locations with significantly higher topographic
316 ruggedness compared to the available landscape (Figure 3, Table 2).

317

318 Some northern quolls primarily used rocky habitat connected by riverbed and spinifex
319 sandplain; riverbed was often associated with rocky habitat at Red Rock (Figure 4a). One male
320 northern quoll used an activity area covering large areas of spinifex sandplain at Python Pool
321 to access patches of rocky habitat (Figure 4b). Others used mainly rocky habitat like at Cattle
322 Gorge (Figure 4c), while one female had an activity area with high cover of *Acacia* stands at
323 De Grey Ridge (Figure 4d, Table S4).

324

325 **Determinants of activity area size**

326 The model “spinifex sandplain” was the top-ranked model (w_i AICc = 0.56) and explained 20%
327 of the variability in activity area size (Table 3). This model showed that northern quoll activity
328 area increased in size when the percentage cover of spinifex sandplain was higher (Figure 5).

329 **Discussion**

330 We investigated the movement ecology of the endangered northern quoll in an arid landscape
331 to identify their preferred habitat and drivers of activity area size. As predicted, northern quolls
332 located their short-term activity areas in habitats that were more rugged, characterised by
333 higher percentage cover of rocky habitat and riverbed than the available landscape. Northern
334 quolls also selected activity areas in locations with a lower percentage cover of spinifex
335 sandplain than the available landscape, and activity areas increased in size when they contained
336 a higher percentage cover of spinifex sandplain. Our findings support those of previous studies
337 which suggest rugged rocky areas provide critical habitat for the Pilbara northern quoll (Moore
338 *et al.* 2021a), and are likely rich in key resources compared to spinifex sandplain. Together
339 these results have important implications for the conservation of this species, particularly in
340 terms of the loss of rugged rocky habitat.

341
342 As predicted, northern quolls selected activity areas in locations with higher percentage cover
343 of rocky habitat and in areas which were more topographically rugged than the available
344 landscape. This supports findings from other studies and confirms that northern quolls and
345 many other critical weight range mammals (CWR, 35–5500 g) (Murphy and Davies 2014)
346 persist in rugged, rocky habitat at a landscape scale (Burbidge and McKenzie 1989; Hernandez-
347 Santin and Fisher 2022; McDonald *et al.* 2017; Molloy *et al.* 2017; Moore *et al.* 2019;
348 Oakwood 2002). Structurally complex rocky habitats in the Pilbara provide several resources
349 and functions to northern quolls which are critical for survival. These include thermally stable
350 denning habitat (Cowan *et al.* 2020b), protection from predators (Hernandez-Santin *et al.*
351 2016), and abundant prey (Dunlop *et al.* 2017). Rocky habitat also protects CWR mammals
352 from fire, grazing, and extreme temperatures (Fitzsimons and Michael 2017; McDonald *et al.*
353 2017). The availability of rugged rocky habitat therefore appears critical for northern quoll
354 persistence, and potential removal of rugged rocky habitat due to human disturbance (e.g.,
355 mining) is likely to heavily impact their persistence (Cramer *et al.* 2016).

356
357 Some habitat types may be avoided because they lack crucial resources or contain risks which
358 animals prefer to avoid (Aldridge and Boyce 2007; Polfus *et al.* 2011). Here, the apparent
359 avoidance of spinifex sandplain by northern quolls is likely explained by increased predation
360 risk in this habitat type and the landscape of fear, which suggests that animals move between
361 resource patches more regularly in areas close to shelter, due to greater perceived safety

362 (Bleicher and Dickman 2020; Laundré *et al.* 2001). For example, feral cats are most successful
363 at hunting in open habitats, where prey is more exposed (McGregor *et al.* 2015; Moseby *et al.*
364 2021; Stobo-Wilson *et al.* 2020), such as spinifex sandplain. Hernandez-Santin *et al.* (2016)
365 showed that feral cats frequently used flat, open spinifex sandplain in their Pilbara ranges and
366 northern quolls avoided areas used by cats spatially and temporally. Moving through spinifex
367 sandplain is likely risky for the smaller quoll, due to the increased chance of intraguild
368 predation (Virgós *et al.* 2020). Reducing the predation risk by feral cats through control
369 programs could benefit quolls by enabling them to make greater use of spinifex sandplains and
370 reducing their reliance on fragmented rocky habitat. For example, after feral cat baiting in the
371 Pilbara, northern quolls were detected using lowland habitats most frequently used by feral
372 cats, likely due to reduced predation pressure (Palmer *et al.* 2021). Similarly, on Groote
373 Eylandt—an island in the Northern Territory with a low abundance of northern quoll
374 predators—northern quolls occupied, had better body condition, and fed within a broader
375 dietary niche within savanna woodland compared to rocky habitat (Thomas *et al.* 2021).

376

377 The rocky habitat preferred by northern quolls [in the presence of feral cats] in the Pilbara is
378 naturally fragmented by spinifex sandplain and (sometimes) by riverbed (Moore *et al.* 2021b;
379 Van Vreeswyk *et al.* 2004). Therefore, northern quolls must travel through these habitats to
380 reach isolated rocky habitat patches. When present, northern quolls selected activity areas in
381 locations with higher percentage cover of riverbed. Conversely, activity areas were larger when
382 they contained higher percentage cover of spinifex sandplain. Spinifex sandplain covers great
383 expanses between rocky habitat and does not offer much protection to northern quolls, with a
384 lack of denning structures or shelter due to low habitat complexity (Hernandez-Santin *et al.*
385 2022; Moore *et al.* 2021b). The increased travel time caused by having large amounts of
386 spinifex sandplain within their activity areas likely exacerbates the already increased risk of
387 predation for northern quolls in this habitat, and may negatively affect their foraging efficiency
388 or fitness (Perry and Pianka 1997). This is supported by the fact that northern quolls in the
389 Pilbara are less abundant in landscapes where rocky habitat is more fragmented (Moore *et al.*
390 2022). A return to landscape management techniques, such as traditional mosaic burning, may
391 reduce the large-scale burning of spinifex sandplain, creating increased habitat complexity
392 (Greenwood *et al.* 2021). When coupled with effective feral cat management (Cowan *et al.*
393 2020a), this may decrease feral cat success in spinifex sandplain and increase the usability of
394 this habitat by northern quolls (Doherty *et al.* 2015)—like mosaic burning has done for other

395 small Australian species (Bliege Bird *et al.* 2013; Holland and Bennett 2007; McDonald *et al.*
396 2016).

397

398 The selection of areas with increased cover of riverbed by northern quolls is likely because
399 riverbed is often associated with rocky habitat and may facilitate movement and foraging
400 opportunities (Ruprecht 1996). Hernandez-Santin *et al.* (2016) found that the distribution of
401 northern quolls in the Pilbara was positively associated with creek lines, but the distribution of
402 feral cats was not, highlighting potential benefits of using this habitat for quolls, as for many
403 small terrestrial vertebrates (Sánchez-Montoya *et al.* 2016). However, this habitat is also likely
404 important for the dispersal of larger predators of the northern quoll in some instances, including
405 feral cats and dingoes (*Canis dingo*) (Williamson *et al.* 2021; Wysong *et al.* 2020). Riverbeds
406 may also offer food for northern quolls. Here, riverbeds were dry, but often hold surface water
407 in the form of puddles for much longer than the surrounding landscape (Smit and Grant 2009).
408 In a mesic environment in Queensland, Pollock (1999) found that ~60% of northern quoll
409 locations were less than 200 m from permanent water, while Hill and Ward (2010) noted that
410 in the Northern Territory there was higher prey availability for northern quolls near water
411 sources. Therefore, riverbeds may facilitate a form of landscape complementation for northern
412 quolls, where quolls benefit from the resources available within two key habitats (i.e., rocky
413 habitat and riverbed) (Dunning *et al.* 1992; Nimmo *et al.* 2019). Previously, emphasis has been
414 placed on protecting or attempting to replicate only rocky habitat for northern quolls (Cowan
415 *et al.* 2020b). However, this emphasises the importance of considering potential dispersal
416 routes and supplemental foraging habitats when planning for northern quoll conservation and
417 management (Bennett 1990; Doherty and Driscoll 2018).

418

419 Our study adds to the growing body of knowledge that suggests that northern quolls require
420 rugged, rocky habitat for survival in the Pilbara, and that their space use is driven by selection
421 for habitats which provide shelter from larger predators such as feral cats. This study also
422 provides a baseline for future studies to investigate how human disturbances such as fire,
423 mining, and agriculture influence northern quoll movement and space use (Moore *et al.* 2021a).
424 The destruction of complex rugged habitat or efficient movement corridors, and replacement
425 with simple habitat—such as cleared land or spinifex sandplain—will likely have dramatically
426 negative effects on northern quolls, including expelling local populations, or having
427 cumulative impacts on the broader population by limiting movement or causing populations to
428 become isolated. Alternatively, it may force northern quolls to travel longer distances to gain

429 the resources needed for survival, potentially decreasing individual body condition and leaving
430 quolls exposed to increased predation, risk of fire, and grazing pressures. The conservation of
431 northern quolls in the Pilbara should value existing rugged, rocky habitat which provides
432 important food resources and protection from predation, as well as efficient movement
433 pathways such as riverbeds that facilitate dispersal. Spinifex sandplain may also offer foraging
434 resources for northern quolls in the Pilbara, but currently, predation risk is likely driving its'
435 avoidance. Management actions to increase complexity of spinifex sandplain may drive higher
436 use of this habitat by northern quolls, and all conservation actions should be coupled with
437 effective management of invasive predators such as feral cats.

438 **Acknowledgements**

439 We acknowledge the Karriyarra, Ngarluma, and Nyamal people as the Traditional Owners of
440 the land where northern quolls were trapped and tracked. We also thank the Department of
441 Biodiversity, Conservation and Attractions (DBCA), Biologic Environmental, Roy Hill, BHP,
442 De Grey Mining, and Colin and Betty Brierly of Indee Station for access to field sites and data.
443 Thank you to Harriet Davie for assisting with and facilitating much of this fieldwork. All
444 animal capture and handling was undertaken with ethics approval from Charles Sturt
445 University (A18034), the University of Queensland (SBS/348/12/ARC), the Department of
446 Environment and Conservation (AEC2011/14, AEC 2014/19), and DBCA (AEC 2017/23,
447 AEC 2020/21D). Relevant research permits were also obtained from DBCA (SF009747, 08-
448 002376-1).

449

450 **Data availability statement**

451 Data used in this study have not been published publicly to protect this cryptic, endangered
452 species. Each dataset is managed by separate authors and organisations; therefore, data can be
453 requested by contacting the respective authors of this study.

454

455 **Conflict of interest**

456 The authors declare no conflict of interest.

457

458 **Declaration of funding**

459 Fieldwork to collect the data used in this study was funded by the Department of Biodiversity,
460 Conservation and Attractions (DBCA), Charles Sturt University (CSU), Roy Hill, BHP, the
461 Australian Research Council, the University of Queensland, Consejo Nacional de Ciencia y
462 Tecnologia (CONACYT, Mexico), the Holsworth Wildlife Research Endowment (ANZ
463 Trustees), and the Australian Government's National Environmental Science Program (NESP)
464 through the Threatened Species Recovery Hub.

465 **References**

- 466 Aldridge, C.L., and Boyce, M.S. (2007) Linking occurrence and fitness to persistence: Habitat-based
467 approach for endangered greater sage-grouse. *Ecological Applications* **17**(2), 508–526.
- 468
469 Bates, D., Maechler, M., Bolker, B., and Walker, S. (2015) Fitting Linear Mixed-Effects Models
470 Using lme4. *Journal of Statistical Software* **67**(1), 1–48.
- 471
472 Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R.H.B., Singmann, H., Dai, B., and
473 Scheipl, F. (2020) Package ‘lme4’.
- 474
475 Bates, D.M. (2010) 'lme4: Mixed-effects modeling with R.' (Springer New York: Madison,
476 Wisconsin, USA)
- 477
478 Beasley, J.C., and Rhodes, O.E. (2010) Influence of patch- and landscape-level attributes on the
479 movement behavior of raccoons in agriculturally fragmented landscapes. *Canadian Journal of*
480 *Zoology* **88**(2), 161–169.
- 481
482 Bennett, A.F. (1990) Habitat corridors and the conservation of small mammals in a fragmented forest
483 environment. *Landscape Ecology* **4**(2), 109–122.
- 484
485 Biologic (2016) Cattle Gorge and Callawa West Vertebrate Fauna Studies. Report prepared for BHP
486 Billiton Iron Ore Pty Ltd: Biologic, Perth.
- 487
488 Bjørneraas, K., Van Moorter, B., Rolandsen, C.M., and Herfindal, I. (2010) Screening Global
489 Positioning System Location Data for Errors Using Animal Movement Characteristics. *The Journal of*
490 *Wildlife Management* **74**(6), 1361–1366.
- 491
492 Bleicher, S.S. (2017) The landscape of fear conceptual framework: definition and review of current
493 applications and misuses. *PeerJ* **5**, e3772.
- 494
495 Bleicher, S.S., and Dickman, C.R. (2020) On the landscape of fear: shelters affect foraging by
496 dunnarts (Marsupialia, Sminthopsis spp.) in a sandridge desert environment. *Journal of Mammalogy*
497 **101**(1), 281-290.
- 498
499 Bliege Bird, R., Taylor, N., Coddling, B.F., and Bird, D.W. (2013) Niche construction and Dreaming
500 logic: aboriginal patch mosaic burning and varanid lizards (*Varanus gouldii*) in Australia.
501 *Proceedings. Biological sciences* **280**(1772), 20132297-20132297. [In eng]
- 502
503 Blundell, G.M., Maier, J.A.K., and Debevec, E.M. (2001) Linear home ranges: Effects of smoothing,
504 sample size, and autocorrelation on kernel estimates. *Ecological Monographs* **71**(3), 469–489.
- 505
506 Braithwaite, R.W., and Griffiths, A.D. (1994) Demographic variation and range contraction in the
507 northern quoll, *Dasyurus hallucatus* (Marsupialia : Dasyuridae). *Wildlife Research* **21**(2), 203–217.
- 508
509 Brown, J.S. (1988) Patch use as an indicator of habitat preference, predation risk, and competition.
510 *Behavioral Ecology and Sociobiology* **22**(1), 37-47.

511
512 Burbidge, A.A., and McKenzie, N.L. (1989) Patterns in the modern decline of western Australia's
513 vertebrate fauna: Causes and conservation implications. *Biological Conservation* **50**(1), 143-198.

514
515 Bureau of Meteorology (2020) Climate Data Online. (Accessed 30 July 2020).

516
517 Burnham, K.P., and Anderson, D.R. (2001) Kullback-Leibler information as a basis for strong
518 inference in ecological studies. *Wildlife Research* **28**, 111-119.

519
520 Carwardine, J., Nicol, S., Van Leeuwen, S., Walters, B., Firn, J., Reeson, A., Martin, T.G., and
521 Chades, I. (2014) Priority threat management for Pilbara species of conservation significance. CSIRO
522 Ecosystems Sciences, No. 1486302785, Brisbane.

523
524 Cook, A. (2010) Habitat use and home-range of the northern quoll, *Dasyurus hallucatus*: effects of
525 fire. The University of Western Australia, Perth

526
527 Cowan, M., Moro, D., Anderson, H., Angus, J., Garretson, S., and Morris, K. (2020a) Aerial baiting
528 for feral cats is unlikely to affect survivorship of northern quolls in the Pilbara region of Western
529 Australia. *Wildlife Research* **47**(8), 589-598.

530
531 Cowan, M.A., Dunlop, J.A., Turner, J.M., Moore, H.A., and Nimmo, D.G. (2020b) Artificial refuges
532 to combat habitat loss for an endangered marsupial predator: How do they measure up? *Conservation
533 Science and Practice* **2**(6), e204.

534
535 Cramer, V.A., Dunlop, J., Davis, R.A., Ellis, R., Barnett, B., Cook, A., Morris, K., and van Leeuwen,
536 S. (2016) Research priorities for the northern quoll (*Dasyurus hallucatus*) in the Pilbara region of
537 Western Australia. *Australian Mammalogy* **38**(2), 135-148.

538
539 Dellinger, J.A., Cristescu, B., Ewanyk, J., Gammons, D.J., Garcelon, D., Johnston, P., Martins, Q.,
540 Thompson, C., Vickers, T.W., Wilmers, C.C., Wittmer, H.U., and Torres, S.G. (2020) Using
541 Mountain Lion Habitat Selection in Management. *The Journal of Wildlife Management* **84**(2), 359-
542 371.

543
544 Doherty, T.S., Dickman, C.R., Nimmo, D.G., and Ritchie, E.G. (2015) Multiple threats, or
545 multiplying the threats? Interactions between invasive predators and other ecological disturbances.
546 *Biological Conservation* **190**, 60-68.

547
548 Doherty, T.S., and Driscoll, D.A. (2018) Coupling movement and landscape ecology for animal
549 conservation in production landscapes. *Proceedings of the Royal Society B: Biological Sciences*
550 **285**(1870), 20172272.

551
552 Doherty, T.S., Fist, C.N., and Driscoll, D.A. (2019) Animal movement varies with resource
553 availability, landscape configuration and body size: a conceptual model and empirical example.
554 *Landscape Ecology* **34**(3), 603-614.

555

556 Douma, J.C., and Weedon, J.T. (2019) Analysing continuous proportions in ecology and evolution: A
557 practical introduction to beta and Dirichlet regression. *Methods in Ecology and Evolution* **10**(9),
558 1412–1430.

559

560 Dunlop, J., Cook, A., and Morris, K. (2014) Pilbara northern quoll project: surveying and monitoring
561 *Dasyurus hallucatus* in the Pilbara, Western Australia. Department of Parks and Wildlife, Perth.

562

563 Dunlop, J., Rayner, K., and Doherty, T.S. (2017) Dietary flexibility in small carnivores: a case study
564 on the endangered northern quoll, *Dasyurus hallucatus*. *Journal of Mammalogy* **98**(3), 858–866.

565

566 Dunning, J.B., Danielson, B.J., and Pulliam, H.R. (1992) Ecological processes that affect populations
567 in complex landscapes. *Oikos* **65**(1), 169–175.

568

569 ESRI (2021) World Imagery, (Featuring Earthstar Geographics (TerraColor NextGen) imagery).
570 (Accessed 30 July 2020).

571

572 Fancourt, B.A., Hawkins, C.E., Cameron, E.Z., Jones, M.E., and Nicol, S.C. (2015) Devil Declines
573 and Catastrophic Cascades: Is Mesopredator Release of Feral Cats Inhibiting Recovery of the Eastern
574 Quoll? *PLOS ONE* **10**(3).

575

576 Fitzsimons, J.A., and Michael, D.R. (2017) Rocky outcrops: A hard road in the conservation of
577 critical habitats. *Biological Conservation* **211**, 36–44.

578

579 Gallant, J., Dowling, T., and Read, A. (2009) 1 second SRTM Level 2 Derived Digital Elevation
580 Model v1.0. Geoscience Australia, Canberra.

581

582 Gardiner, R., Proft, K., Comte, S., Jones, M., and Johnson, C.N. (2019) Home range size scales to
583 habitat amount and increasing fragmentation in a mobile woodland specialist. *Ecology and Evolution*
584 **9**(24), 14005–14014.

585

586 Girard, I., Ouellet, J.-P., Courtois, R., Dussault, C., and Breton, L. (2002) Effects of Sampling Effort
587 Based on GPS Telemetry on Home-Range Size Estimations. *The Journal of Wildlife Management*
588 **66**(4), 1290–1300.

589

590 Greenwood, L., Bliege Bird, R., and Nimmo, D. (2021) Indigenous burning shapes the structure of
591 visible and invisible fire mosaics. *Landscape Ecology*.

592

593 Haapakoski, M., Sundell, J., and Ylönen, H. (2013) Mammalian predator–prey interaction in a
594 fragmented landscape: weasels and voles. *Oecologia* **173**(4), 1227–1235.

595

596 Harris, S., Cresswell, W., Forde, P., Trehwella, W., Woollard, T., and Wray, S. (1990) Home-range
597 analysis using radio-tracking data - a review of problems and techniques particularly as applied to the
598 study of mammals. *Mammal Review* **20**, 97–123.

599

600 Hazen, E.L., Abrahms, B., Brodie, S., Carroll, G., Welch, H., and Bograd, S.J. (2021) Where did they
601 not go? Considerations for generating pseudo-absences for telemetry-based habitat models. *Movement*
602 *Ecology* **9**(1), 5.

603
604 Heiniger, J., Cameron, S.F., Madsen, T., Niehaus, A.C., and Wilson, R.S. (2020) Demography and
605 spatial requirements of the endangered northern quoll on Groote Eylandt. *Wildlife Research* **47**(3),
606 224–238.

607
608 Henderson, M. (2015) The Effects of Mining Infrastructure on Northern quoll Movement and Habitat.
609 Edith Cowan University, Perth

610
611 Hernandez-Santin, L., Dunlop, J.A., Goldizen, A.W., and Fisher, D.O. (2019) Demography of the
612 northern quoll (*Dasyurus hallucatus*) in the most arid part of its range. *Journal of Mammalogy* **100**(4),
613 1191–1198.

614
615 Hernandez-Santin, L., and Fisher, D.O. (2022) Community structure of dasyurid marsupials in the
616 arid Pilbara is consistent with a top-down system, their distribution and abundance depend on that of
617 larger members of the guild. *Journal of Arid Environments* **198**, 104680.

618
619 Hernandez-Santin, L., Goldizen, A.W., and Fisher, D.O. (2016) Introduced predators and habitat
620 structure influence range contraction of an endangered native predator, the northern quoll. *Biological*
621 *Conservation* **203**, 160–167.

622
623 Hernandez-Santin, L., Goldizen, A.W., and Fisher, D.O. (2022) Northern quolls in the Pilbara persist
624 in high-quality habitat, despite a decline trajectory consistent with range eclipse by feral cats.
625 *Conservation Science and Practice*, e12733.

626
627 Hernandez-Santin, L., Henderson, M., Molloy, S.W., Dunlop, J.A., and Davis, R.A. (2020) Spatial
628 ecology of an endangered carnivore, the Pilbara northern quoll. *Australian Mammalogy* **43**, 235–242.

629
630 Hijmans, R.J., Van Etten, J., Cheng, J., Mattiuzzi, M., Sumner, M., Greenberg, J.A., Lamigueiro,
631 O.P., Bevan, A., Racine, E.B., and Shortridge, A. (2015) Package ‘raster’.

632
633 Hill, B.M., and Ward, S.J. (2010) National recovery plan for the northern quoll *Dasyurus hallucatus*.
634 *Department of Natural Resources, Environment, The Arts and Sport, Darwin*.

635
636 Holland, G.J., and Bennett, A.F. (2007) Occurrence of small mammals in a fragmented landscape: the
637 role of vegetation heterogeneity. *Wildlife Research* **34**(5), 387–397.

638
639 Huck, M., Davison, J., and Roper, T.J. (2008) Comparison of two sampling protocols and four home-
640 range estimators using radio-tracking data from urban badgers *Meles meles*. *Wildlife Biology* **14**(4),
641 467–477.

642
643 Ibbett, M., Woinarski, J.C.Z., and Oakwood, M. (2018) Declines in the mammal assemblage of a
644 rugged sandstone environment in Kakadu National Park, Northern Territory, Australia. *Australian*
645 *Mammalogy* **40**(2), 181–187.

646
647 Kernohan, B.J., Gitzen, R.A., and Millspaugh, J.J. (2001) Analysis of animal space use and
648 movements. In 'Radio tracking and animal populations.' pp. 125–166. (Academic Press)

649
650 Kie, J.G. (2013) A rule-based ad hoc method for selecting a bandwidth in kernel home-range
651 analyses. *Animal Biotelemetry* **1**(1), 13.

652
653 King, D. (1989) An assessment of the hazard posed to northern quolls (*Dasyurus hallucatus*) by aerial
654 baiting with 1080 to control dingoes. *Wildlife Research* **16**(5), 569–574.

655
656 Kuznetsova, A., Brockhoff, P.B., and Christensen, R.H.B. (2015) Package ‘lmerTest’.

657
658 Laundré, J.W., Hernández, L., and Altendorf, K.B. (2001) Wolves, elk, and bison: reestablishing the
659 "landscape of fear" in Yellowstone National Park, U.S.A. *Canadian Journal of Zoology* **79**(8), 1401-
660 1409.

661
662 Mac Nally, R., Duncan, R.P., Thomson, J.R., and Yen, J.D.L. (2018) Model selection using
663 information criteria, but is the “best” model any good? *Journal of Applied Ecology* **55**(3), 1441–1444.

664
665 Martin, J.K., and Martin, A.A. (2007) Resource Distribution Influences Mating System in the Bobuck
666 (*Trichosurus cunninghami*: Marsupialia). *Oecologia* **154**(1), 227–236.

667
668 Maslin, B.R., and van Leeuwen, S. (2008) New taxa of Acacia (Leguminosae: Mimosoideae) and
669 notes on other species from the Pilbara and adjacent desert regions of Western Australia. *Nuytsia* **18**,
670 139–188.

671
672 Mazerolle, M.J., and Mazerolle, M.M.J. (2017) Package ‘AICcmodavg’.

673
674 McDonald, P.J., Nano, C.E.M., Ward, S.J., Stewart, A., Pavey, C.R., Luck, G.W., and Dickman, C.R.
675 (2017) Habitat as a mediator of mesopredator-driven mammal extinction. *Conservation Biology* **31**(5),
676 1183–1191.

677
678 McDonald, P.J., Stewart, A., Schubert, A.T., Nano, C.E.M., Dickman, C.R., and Luck, G.W. (2016)
679 Fire and grass cover influence occupancy patterns of rare rodents and feral cats in a mountain refuge:
680 implications for management. *Wildlife Research* **43**(2), 121-129.

681
682 McGregor, H.W., Legge, S., Jones, M.E., and Johnson, C.N. (2015) Feral cats are better killers in
683 open habitats, revealed by animal-borne video. *PloS one* **10**(8), e0133915.

684
685 McKenzie, N.L., van Leeuwen, S., and Pinder, A.M. (2009) Introduction to the Pilbara Biodiversity
686 Survey, 2002–2007. *Records of the Western Australian Museum, Supplement* **78**(1).

687
688 Michel, E.S., Gullikson, B.S., Brackel, K.L., Schaffer, B.A., Jenks, J.A., and Jensen, W.F. (2020)
689 Habitat selection of white-tailed deer fawns and their dams in the Northern Great Plains. *Mammal*
690 *Research* **65**(4), 825–833.

691

692 Mitchell, L.J., White, P.C.L., and Arnold, K.E. (2019) The trade-off between fix rate and tracking
693 duration on estimates of home range size and habitat selection for small vertebrates. *PLOS ONE*
694 **14**(7), e0219357.

695

696 Molloy, S.W., Davis, R.A., Dunlop, J.A., and van Etten, E.J.B. (2017) Applying surrogate species
697 presences to correct sample bias in species distribution models: a case study using the Pilbara
698 population of the northern quoll. *Nature Conservation* **18**, 27–46.

699

700 Moore, H.A., Dunlop, J.A., Jolly, C.J., Kelly, E., Woinarski, J.C.Z., Ritchie, E.G., Burnett, S., van
701 Leeuwen, S., Valentine, L.E., Cowan, M.A., and Nimmo, D.G. (2021a) A brief history of the northern
702 quoll (*Dasyurus hallucatus*): a systematic review. *Australian Mammalogy*.

703

704 Moore, H.A., Dunlop, J.A., Valentine, L.E., Woinarski, J.C.Z., Ritchie, E.G., Watson, D.M., and
705 Nimmo, D.G. (2019) Topographic ruggedness and rainfall mediate geographic range contraction of a
706 threatened marsupial predator. *Diversity and Distributions* **25**, 1818–1831.

707

708 Moore, H.A., Michael, D.R., Dunlop, J.A., Valentine, L.E., Cowan, M.A., and Nimmo, D.G. (2022)
709 Habitat amount is less important than habitat configuration for a threatened marsupial predator in
710 naturally fragmented landscapes. *Landscape Ecology* **37**, 935–949.

711

712 Moore, H.A., Michael, D.R., Ritchie, E.G., Dunlop, J.A., Valentine, L.E., Hobbs, R.J., and Nimmo,
713 D.G. (2021b) A rocky heart in a spinifex sea: occurrence of an endangered marsupial predator is
714 multiscale dependent in naturally fragmented landscapes. *Landscape Ecology* **36**, 1359–1376.

715

716 Moseby, K.E., Hodgens, P., Peacock, D., Mooney, P., Brandle, R., Lynch, C., West, R., Young, C.M.,
717 Bannister, H., Copley, P., and Jensen, M.A. (2021) Intensive monitoring, the key to identifying cat
718 predation as a major threat to native carnivore (*Dasyurus geoffroii*) reintroduction. *Biodiversity and*
719 *Conservation* **30**(6), 1–25.

720

721 Muff, S., Signer, J., and Fieberg, J. (2020) Accounting for individual-specific variation in habitat-
722 selection studies: Efficient estimation of mixed-effects models using Bayesian or frequentist
723 computation. *Journal of Animal Ecology* **89**(1), 80–92.

724

725 Murphy, B.P., and Davies, H.F. (2014) There is a critical weight range for A ustralia's declining
726 tropical mammals. *Global Ecology and Biogeography* **23**(9), 1058-1061.

727

728 Najera-Zuloaga, J., Lee, D.-J., Arostegui, I., and Najera-Zuloaga, M.J. (2020) Package ‘PROreg’.

729

730 Nimmo, D.G., Avitabile, S., Banks, S.C., Bliege Bird, R., Callister, K., Clarke, M.F., Dickman, C.R.,
731 Doherty, T.S., Driscoll, D.A., Greenville, A.C., Haslem, A., Kelly, L.T., Kenny, S.A., Lahoz-
732 Monfort, J.J., Lee, C., Leonard, S., Moore, H., Newsome, T.M., Parr, C.L., Ritchie, E.G., Schneider,
733 K., Turner, J.M., Watson, S., Westbrooke, M., Wouters, M., White, M., and Bennett, A.F. (2019)
734 Animal movements in fire-prone landscapes. *Biological Reviews* **94**(3), 981–998.

735

736 Oakwood, M. (2002) Spatial and social organization of a carnivorous marsupial *Dasyurus hallucatus*.
737 *Journal of Zoology* **257**(2), 237–248.

738

739 Palmer, R., Anderson, H., Richards, B., Craig, M.D., and Gibson, L. (2021) Does aerial baiting for
740 controlling feral cats in a heterogeneous landscape confer benefits to a threatened native meso-
741 predator? *PLOS ONE* **16**(5), e0251304.

742

743 Pandey, A.C., and Kulhari, A. (2018) 'Semi-supervised spatiotemporal classification and trend
744 analysis of satellite images.' (Springer Singapore: Singapore) 353–363

745

746 Peris, A., Closa, F., Marco, I., Acevedo, P., Barasona, J.A., and Casas-Díaz, E. (2020) Towards the
747 comparison of home range estimators obtained from contrasting tracking regimes: the wild boar as a
748 case study. *European Journal of Wildlife Research* **66**(2), 32.

749

750 Perry, G., and Pianka, E.R. (1997) Animal foraging: past, present and future. *Trends in Ecology &*
751 *Evolution* **12**(9), 360–364.

752

753 Polfus, J.L., Hebblewhite, M., and Heinemeyer, K. (2011) Identifying indirect habitat loss and
754 avoidance of human infrastructure by northern mountain woodland caribou. *Biological Conservation*
755 **144**(11), 2637–2646.

756

757 Pollock, A.B. (1999) Notes on status, distribution and diet of northern quoll *Dasyurus hallucatus* in
758 the Mackay-Bowen area, mideastern Queensland. *Australian Zoologist* **31**(2), 388–395.

759

760 Powell, R.A. (2000) Animal home ranges and territories and home range estimators. *Research*
761 *techniques in animal ecology: controversies and consequences* **442**, 65–110.

762

763 QGIS Development Team (2020) QGIS Geographic Information System. Open Source Geospatial
764 Foundation Project.

765

766 R Core Team (2020) R: A language and environment for statistical computing. *R Foundation for*
767 *Statistical Computing*.

768

769 Ramanaidou, E.R., and Morris, R.C. (2010) A synopsis of the channel iron deposits of the Hamersley
770 Province, Western Australia. *Applied Earth Science* **119**(1), 56–59.

771

772 Riley, S.J., DeGloria, S.D., and Elliot, R. (1999) Index that quantifies topographic heterogeneity.
773 *intermountain Journal of sciences* **5**(1-4), 23–27.

774

775 Ruprecht, J. (1996) Arid Zone Hydrology: Pilbara Region of Western Australia. In '' pp. 301–305)

776

777 Rus, A.I., McArthur, C., Mella, V.S.A., and Crowther, M.S. (2020) Habitat fragmentation affects
778 movement and space use of a specialist folivore, the koala. *Animal Conservation* **24**, 26–37.

779

780 Sánchez-Montoya, M.M., Moleón, M., Sánchez-Zapata, J.A., and Tockner, K. (2016) Dry riverbeds:
781 corridors for terrestrial vertebrates. *Ecosphere* **7**(10), e01508.

782

783 Seaman, D.E., Millsaugh, J.J., Kernohan, B.J., Brundige, G.C., Raedeke, K.J., and Gitzen, R.A.
784 (1999) Effects of Sample Size on Kernel Home Range Estimates. *The Journal of Wildlife*
785 *Management* **63**(2), 739–747.

786
787 Signer, J., and Balkenhol, N. (2015) Reproducible home ranges (rhr): A new, user-friendly R package
788 for analyses of wildlife telemetry data. *Wildlife Society Bulletin* **39**(2), 358–363.

789
790 Signer, J., Balkenhol, N., Ditmer, M., and Fieberg, J. (2015) Does estimator choice influence our
791 ability to detect changes in home-range size? *Animal Biotelemetry* **3**(1), 16.

792
793 Smit, I.P.J., and Grant, C.C. (2009) Managing surface-water in a large semi-arid savanna park: Effects
794 on grazer distribution patterns. *Journal for Nature Conservation* **17**(2), 61–71.

795
796 Squires, J.R., DeCesare, N.J., Olson, L.E., Kolbe, J.A., Hebblewhite, M., and Parks, S.A. (2013)
797 Combining resource selection and movement behavior to predict corridors for Canada lynx at their
798 southern range periphery. *Biological Conservation* **157**, 187–195.

799
800 Stobo-Wilson, A.M., Cremona, T., Murphy, B.P., and Carthew, S.M. (2021) Resource availability
801 drives variation in a marsupial glider’s home-range size. *Journal of Zoology* **315**(2), 199–212.

802
803 Stobo-Wilson, A.M., Stokeld, D., Einoder, L.D., Davies, H.F., Fisher, A., Hill, B.M., Mahney, T.,
804 Murphy, B.P., Stevens, A., Woinarski, J.C.Z., Rangers, B., Rangers, W., and Gillespie, G.R. (2020)
805 Habitat structural complexity explains patterns of feral cat and dingo occurrence in monsoonal
806 Australia. *Diversity and Distributions* **26**(7), 832–842.

807
808 Stratmann, T.S.M., Dejid, N., Calabrese, J.M., Fagan, W.F., Fleming, C.H., Olson, K.A., and Mueller,
809 T. (2021) Resource selection of a nomadic ungulate in a dynamic landscape. *PLOS ONE* **16**(2),
810 e0246809.

811
812 Thomas, H., Cameron, S.F., Campbell, H.A., Micheli-Campbell, M.A., Kirke, E.C., Wheatley, R., and
813 Wilson, R.S. (2021) Rocky escarpment versus savanna woodlands: comparing diet and body
814 condition as indicators of habitat quality for the endangered northern quoll (*Dasyurus hallucatus*).
815 *Wildlife Research* **48**(5), 434–443.

816
817 Tilahun, A., and Teferie, B. (2015) Accuracy assessment of land use land cover classification using
818 Google Earth. *Am. J. Environ. Prot* **4**(4), 193–198.

819
820 USGS (2020) Earth Explorer. (Accessed 30 July 2020).

821
822 Van Vreeswyk, A.M.E., Leighton, K.A., Payne, A.L., and Hennig, P. (2004) An inventory and
823 condition survey of the Pilbara region, Western Australia. Department of Agriculture and Food, Perth.

824
825 Viana, D.S., Granados, J.E., Fandos, P., Pérez, J.M., Cano-Manuel, F.J., Burón, D., Fandos, G.,
826 Aguado, M.Á.P., Figuerola, J., and Soriguer, R.C. (2018) Linking seasonal home range size with
827 habitat selection and movement in a mountain ungulate. *Movement Ecology* **6**(1), 1.

828

829 Virgós, E., Baniandrés, N., Burgos, T., and Recio, M.R. (2020) Intraguild Predation by the Eagle Owl
830 Determines the Space Use of a Mesopredator Carnivore. *Diversity* **12**(9), 359.

831
832 Williamson, S.D., van Dongen, R., Trotter, L., Palmer, R., and Robinson, T.P. (2021) Fishing for
833 Feral Cats in a Naturally Fragmented Rocky Landscape Using Movement Data. *Remote Sensing*
834 **13**(23), 4925.

835
836 Woinarski, J.C.Z., Armstrong, M., Brennan, K., Fisher, A., Griffiths, A.D., Hill, B., Milne, D.J.,
837 Palmer, C., Ward, S., Watson, M., Winderlich, S., and Young, S. (2010) Monitoring indicates rapid
838 and severe decline of native small mammals in Kakadu National Park, northern Australia. *Wildlife*
839 *Research* **37**(2), 116-126.

840
841 Woinarski, J.C.Z., Burbidge, A., and Harrison, P. (2014) 'The action plan for Australian mammals
842 2012.' (CSIRO publishing)

843
844 Wynn, M.L., Clemente, C., Nasir, A.F., and Wilson, R.S. (2015) Running faster causes disaster:
845 trade-offs between speed, manoeuvrability and motor control when running around corners in
846 northern quolls (*Dasyurus hallucatus*). *J Exp Biol* **218**(3), 433–9. [In eng]

847
848 Wysong, M.L., Hradsky, B.A., Iacona, G.D., Valentine, L.E., Morris, K., and Ritchie, E.G. (2020)
849 Space use and habitat selection of an invasive mesopredator and sympatric, native apex predator.
850 *Movement Ecology* **8**(1), 18.

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852

853 **Figure legends**

854 **Figure 1.** A map of the locations of the four sites in the Pilbara region of Western Australia
855 where northern quolls were tracked between 2014 and 2018. Black points represent study sites
856 and white points represent major towns close to study sites. The satellite base map was sourced
857 from ESRI (2021).

858

859 **Figure 2:** Examples of the dominant habitat types at our study sites in the Pilbara region of
860 Western Australia: a) rocky habitat, which often rises above the landscape to form outcrops; b)
861 spinifex sandplain, which fragments rocky habitat and can stretch for kilometres; c) *Acacia*
862 stands, which can form thick patches throughout the rocky spinifex matrix; and d) riverbed,
863 which consists of a sandy base between rocky habitat and vegetation. Photographs: Cowan, M.

864

865 **Figure 3.** Habitat variables significantly selected or avoided by northern quolls were: the
866 proportional cover of a) rocky habitat, b) riverbed, and c) spinifex sandplain, and d) the median
867 topographic ruggedness index (median TRI), Black points represent data values within
868 ‘available’ and ‘used’ northern quoll activity areas., grey points represent outliers, and red
869 asterisks signify a significant difference between ‘used’ and ‘available’ activity areas. Boxplots
870 show the distribution of the data for available and used activity areas.

871

872 **Figure 4.** Habitat maps of the four sites in the Pilbara region of Western Australia with
873 examples of a) two female northern quoll activity areas at Red Rock showing use of rocky
874 habitat, riverbed, and spinifex sandplain; b) a male northern quoll activity area at Python Pool
875 covering rocky habitat and *Acacia* stands but also large amounts of spinifex sandplain; c) a
876 female northern quoll activity area at Cattle Gorge primarily using rocky habitat; and d) a
877 female northern quoll activity area at De Grey Ridge using primarily rocky habitat and *Acacia*
878 stands. Habitat maps were derived from Sentinel-2 imagery (USGS 2020).

879

880 **Figure 5.** The a) coefficients, and b) predicted effects of the top-ranked model (spinifex
881 sandplain) determining northern quoll activity area. Northern quoll activity area was \log_{10}
882 transformed to increase normality. In plot a), points reflect coefficients, thick bars represent
883 the standard error, thin bars represent 95% confidence intervals, and the red dashed line
884 represents the zero line (zero difference from the intercept). All bars which do not touch the

885 zero line are significant. The intercept reflects the reference level: 0% cover of spinifex
886 sandplain. For plot b), the black line represents the predicted effects, and the red band
887 represents the 95% confidence interval.

888

889 **Tables**

890 **Table 1.** The mean and standard error (SE) of short-term activity area size and percentage
 891 cover of each habitat type for all northern quolls, female northern quolls, and male northern
 892 quolls. Means and SE for habitat cover (%) reflect all short-term activity areas (i.e., including
 893 those tracked for less than seven nights). However, short-term activity area size (ha) marked
 894 with an asterisk (*) reflects only activity areas which reached seven nights. Individual
 895 characteristics for each tracking event can be found in Table S4.

Measure	Sex	Short-term activity area size (ha)*	Rocky habitat (%)	Spinifex sandplain (%)	<i>Acacia</i> stands (%)	Riverbed (%)
Mean	All	153.42	23.14	57.09	12.68	4.86
	Female	91.24	27.07	50.95	13.89	4.98
	Male	215.61	13.33	72.44	9.66	4.57
SE	All	38.69	3.12	3.86	3.94	1.27
	Female	24.39	0.03	0.04	0.05	0.02
	Male	61.75	5.97	4.55	2.74	1.78

896

897 **Table 2.** Outputs from BBMMs and GLMMs for northern quoll habitat selection. Habitat types
 898 in bold denote that used activity areas differed significantly to the intercept (available activity
 899 areas). SE represents the standard error.

Habitat variable	Activity area type	Coefficient	SE	<i>t</i> value	<i>p</i> value
Rocky habitat	Intercept	-2.48	0.09	-27.88	<0.001
	Used	1.08	0.25	4.32	<0.001
Riverbed	Intercept	-9.55	0.12	-81.62	<0.001
	Used	0.92	0.31	2.92	0.004
Spinifex sandplain	Intercept	0.87	0.07	11.69	<0.001
	Used	-0.79	0.23	-3.41	<0.001
<i>Acacia</i> stands	Intercept	-2.44	0.06	-41.68	<0.001
	Used	0.19	0.18	1.03	0.302
Median TRI	Intercept	0.63	0.31	2.00	0.140
	Used	0.79	0.18	4.48	<0.001

900

901

902 **Table 3.** Model selection outputs for possible determinants of northern quoll activity area size,
 903 offset for the number of nights tracked. Rocky habitat, riverbed, and spinifex sandplain are the
 904 proportion of the activity area comprising that habitat type, median TRI is the median
 905 topographic ruggedness index of the activity area, sex is whether the quoll was male or female,
 906 and weight is the body weight of the individual. Models are ranked in descending order from
 907 best to least supported. K represents the number of estimated parameters for each model, AICc
 908 represents the Akaike’s Information Criterion, Δ AICc indicates the delta AIC value, and w_i
 909 AICc indicates the level of support for each model. Log-likelihood and model fit are also
 910 provided for each model. Models in bold are those which had substantial support (Δ AICc <2,
 911 Burnham and Anderson 2001; Mac Nally *et al.* 2018).

Rank	Model	K	AICc	Δ AICc	w_i AICc	Log-likelihood	r^2
1	spinifex sandplain	4	43.05	0	0.56	-15.3	0.20
2	median TRI	4	45.84	2.79	0.14	-16.7	0.02
3	riverbed	4	46.5	3.45	0.1	-17.03	0.13
4	rocky habitat	4	46.98	3.93	0.08	-17.27	0.03
5	weight	4	47.47	4.42	0.06	-17.51	0.04
6	sex	4	47.74	4.7	0.05	-17.65	0.01

912

913

914 **Short summary for online Table of Contents**

915 To effectively conserve species, we must have a good understanding of the key habitats that
916 they use or avoid. We investigated the habitat use of the endangered northern quoll and found
917 that they primarily selected areas with higher proportions of rugged, rocky habitat and riverbed,
918 and avoided areas with higher proportions of spinifex sandplain—a habitat which caused quolls
919 to have larger activity areas. These findings will inform conservation efforts to increase
920 protection of key habitats for the endangered northern quoll.

921