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Leopard (*Panthera pardus*) density in southern Mozambique: Evidence from spatially explicit capture-recapture in Xonghile Game Reserve

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Abstract:	Rigorous status estimates of large carnivore populations are necessary to inform their management and help evaluate the effectiveness of conservation interventions. The African leopard (<i>Panthera pardus</i>) faces rising anthropogenic pressures across most of its contracting sub-Saharan range, but the scarcity of reliable population estimates means that management decisions often have to rely on expert opinion or educated guesses. This is particularly true for Mozambique, where as a result of prolonged conflict very little is known on the ecology or conservation status of leopard populations across the country. We used camera trapping and spatially explicit capture-recapture models to provide a leopard density estimate in Xonghile Game Reserve, southern Mozambique, part of the

Greater Limpopo Transfrontier conservation initiative. The estimated population density was of 2.60 (SE= ± 0.96) leopards per 100 km². Our study provides a baseline leopard density for the region, as well as the first empirical density estimate in southern Mozambique. In addition, our results suggest that current methods used to set trophy hunting quotas for leopard, both in Mozambique and elsewhere in Africa, might be leading to overinflated quotas, and highlight the importance of robust empirical data in guiding conservation policy.

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1 **TITLE:** Leopard (*Panthera pardus*) density in southern Mozambique: Evidence from spatially
2 explicit capture-recapture in Xonghile Game Reserve

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35 **ABSTRACT**

36 Rigorous status estimates of large carnivore populations are necessary to inform their
37 management and help evaluate the effectiveness of conservation interventions. The African
38 leopard (*Panthera pardus*) faces rising anthropogenic pressures across most of its contracting sub-
39 Saharan range, but the scarcity of reliable population estimates means that management decisions
40 often have to rely on expert opinion or educated guesses. This is particularly true for
41 Mozambique, where as a result of prolonged conflict very little is known on the ecology or
42 conservation status of leopard populations across the country. We used camera trapping and
43 spatially explicit capture-recapture models to provide a leopard density estimate in Xonghile
44 Game Reserve, southern Mozambique, part of the Greater Limpopo Transfrontier conservation
45 initiative. The estimated population density was of 2.60 (SE= ± 0.96) leopards per 100 km². Our
46 study provides a baseline leopard density for the region, as well as the first empirical density
47 estimate in southern Mozambique. In addition, our results suggest that current methods used to
48 set trophy hunting quotas for leopard, both in Mozambique and elsewhere in Africa, might be
49 leading to overinflated quotas, and highlight the importance of robust empirical data in guiding
50 conservation policy.

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60 **INTRODUCTION**

61 The leopard (*Panthera pardus*) is vulnerable to extinction in fragmented landscapes due to its low
62 densities, large spatial requirements and potential for conflict with humans (Nowell & Jackson,
63 1996; Balme *et al.*, 2010). Leopard populations in Africa are increasingly threatened by growing
64 anthropogenic pressures, leading to a rising conservation concern and calls for reliable
65 population estimates to better inform conservation management (Jacobson *et al.*, 2016). In the
66 absence of robust population estimates, management decisions are often reliant on expert
67 opinion or educated guesses, making it difficult to identify areas of concern, prioritise
68 conservation investments, and evaluate the effectiveness of interventions (Balme *et al.*, 2014;
69 Gray & Prum, 2012).

70 In this context, density estimation, such as through capture-recapture modelling, has become a
71 key process in wildlife ecology, conservation, and management (Gray & Prum, 2012). Initially,
72 capture-recapture techniques estimated abundance rather than density, and relied on estimating
73 the survey's effective sampled area to obtain the latter. However, no theoretical basis exists for
74 this process, and the reliability of this approach is therefore questionable (Efford, 2004; Borchers
75 & Efford, 2008; Royle *et al.*, 2009). Recently developed methodologies, know as spatially-explicit
76 capture-recapture (SECR) overcome these issues by estimating density directly as an explicit
77 parameter (Efford, 2004; Royle *et al.*, 2009)

78 Since being first applied to tiger populations in India (Karanth, 1995), capture-recapture
79 techniques have been employed to obtain density estimates of most large carnivores, including
80 for leopards in various African countries, such as South Africa (Balme *et al.*, 2009; Chase-Grey *et al.*,
81 2013; Swanepoel *et al.*, 2015), Gabon (Henschel, 2011), Tanzania (Cavallo, 1993), and
82 Namibia (Stein *et al.*, 2011). Nevertheless, there is still paucity of such data across much of the
83 continent, precluding effective conservation management (Balme *et al.*, 2014). This is particularly

84 the case for Mozambique, where armed conflicts during much of the latter half of the 20th
85 century contributed to large declines in wildlife populations across the country (Hatton *et al.*
86 2001), and considerably hindered conservation efforts. As a result, very little research has been
87 conducted on the status, distribution or ecology of the leopard in Mozambique.

88 Leopards are legally hunted for trophies in several locations in Mozambique, with the current
89 quota set at 120 permits per annum (CITES, 2007). This quota is based on efforts to estimate the
90 overall abundance of leopards in Mozambique by Martin & de Meulenaer (1988), who employed
91 a predictive model to estimate a country-wide population of 37,542 leopards, based on an
92 average density of 0.10/km² (10 leopards per 100 km²). Such estimates have been widely rejected
93 as exaggerated for a number of reasons, including omitting from the model critical factors such
94 as anthropogenic mortalities and prey availability, and relying on the assumption that leopards
95 occur at maximum potential densities in all available habitats (Jackson, 1989; Balme *et al.*, 2010).
96 Nevertheless, this approach was employed as a justification for the most recent increase in
97 trophy hunting quota, with a lack of alternative in-country estimates of population densities cited
98 as the principal reason for this (CITES, 2007). Consequently, more accurate assessments of
99 leopard populations in Mozambique are needed to assess the reliability of current quota setting
100 methods in the country, and to ensure that future changes in trophy hunting quotas are based on
101 robust population data.

102 Here we use a closed-population SECR methodology to estimate density of leopards in Xonghile
103 Game Reserve (XGR), a legally protected area in southern Mozambique. The aim of the study
104 was to obtain the first empirical density estimate for a leopard population in southern
105 Mozambique, and provide information that can guide management and act as a baseline to assess
106 conservation interventions. Finally, the implications of findings for trophy hunting in
107 Mozambique are explored.

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111 **STUDY AREA**

112 Xonghile Game Reserve (Fig. 1) is a legally protected area in southern Mozambique. Its
113 northern-most border is located approximately 13 km south of Limpopo National Park's (LNP)
114 southern border, the country's largest national park. XGR is unfenced, bordering South Africa's
115 Kruger National Park (KNP) to the west and unprotected land to the north, east and south. The
116 reserve covers approximately 450 km², and is part of the Greater Limpopo Transfrontier
117 Conservation Area (GLTFCA), a trans-boundary initiative where protected parks and reserves in
118 Mozambique, South Africa and Zimbabwe are linked by non-protected areas. The predominant
119 habitat in XGR consists of sand plains ('sandveld') characterized by low woodlands and thickets
120 on deep sandy soils, as well as short-grass 'pans' (seasonally flooded depressions). Although large
121 mammal populations in the region were severely depleted during the country's many years of
122 armed conflicts (1964-1992; Hanks, 2000), the removal of fencing along the KNP border in
123 recent years has provided the potential for movement of wildlife into the area. No human
124 population permanently resides in XGR, with the main anthropogenic impacts coming from
125 relatively low levels of poaching for bushmeat, anti-poaching efforts, and the low levels of
126 tourism the reserve experiences (Andresen & Everatt; unpublished data). Trophy hunting does
127 not currently take place in XGR.

128 **Figure 1 here**

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130 **METHODS**

131 **Camera Trapping**

132 29 digital motion-activated cameras of multiple models (Reconyx HC500, Spy Point Tiny-W2,
133 Bushnell Trophy Cam) were deployed at 26 stations over an area of c. 300 km² in XGR (Fig. 1),

134 between August 24 - November 23, 2012. Twenty-three stations had a single camera at the
135 station, while at three stations two cameras were deployed.

136 The majority of stations were located at a distance of between 0.5-3 km from one other, ensuring
137 that multiple cameras were likely to be present in an individual's home range. This was the case
138 for all but three stations, which were placed between 5 and 6 km from the nearest station. While
139 there was therefore a small possibility that an individual's home range did not contain a station,
140 SECR models allow for the presence of such 'holes' in the trap array when estimating density
141 (Borchers & Efford, 2008), and low prey densities in the study area (Andresen & Everatt,
142 *unpublished data*) suggest this is unlikely. Cameras were set on trees along roads and game trails at
143 a height of 35cm. The survey length of 92 days was considered adequate for assuming
144 demographic closure, consistently with numerous previous studies of large felids (*e.g.* Karanth,
145 1995; Alexander *et al.*, 2015; Boron *et al.*, 2016).

146 **Density Estimation**

147 Density was modelled in a SECR framework, using the package *secr* (Efford, 2015) running in R
148 v3.2.3 (R Core Development Team, 2015). A maximum-likelihood framework was chosen over a
149 Bayesian one as it provides results comparable with other studies (Tobler & Powell, 2013; Noss
150 *et al.*, 2013) with quicker computation times (Efford, 2015).

151 Leopards were identified from their pelage patterns and sexed by visual inspection of external
152 genitalia. The flank with the greater number of captures (left) was chosen for identification of
153 individual leopards. Individual spatial capture and trap effort histories were developed following
154 the recommended procedures (Efford, 2015), with each day (24 hours) treated as a separate
155 sampling occasion, as recommended by recent findings (Goldberg *et al.*, 2015). Information on
156 varying effort from different camera stations (exact number of days active) was included in order
157 to improve estimates of detection probability. The buffer width around the trapping grid was
158 increased until density estimates stabilised, ensuring that no individual outside of the buffer area

159 could be captured, and a half-normal detection function was fitted to the distance between home
160 range centre and station. This is the most commonly used function in spatial capture-recapture
161 analyses (Efford, 2004; Boron *et al.*, 2016), and describes the probability of capture (P) of an
162 individual i at a trap j as a function of distance (d) from the activity centre of the individual to the
163 trap, as follows: $P_{ij} = g_0 \exp(-d_{ij}^2/(2\sigma^2))$, where g_0 is the probability of capture at exactly the
164 home range centre, and σ is a spatial parameter related to home range size (Efford, 2004).
165 A Bernoulli or binomial encounter model was fitted to the data, as this is most relevant to
166 camera trapping studies; under this model, an individual can be recorded at different camera
167 stations during one sampling occasion, but only once at each station (Royle *et al.*, 2009; Noss *et*
168 *al.*, 2013).

169 Given that leopard populations have been shown to have unequal ranging patterns between
170 sexes (Bailey, 1993; Kittle *et al.*, 2017), in turn potentially impacting capture parameters, sex was
171 modelled as a covariate (Sollmann *et al.*, 2011; Tobler & Powell, 2013; Goldberg *et al.*, 2015). This
172 was achieved by fitting a hybrid mixture model, which accommodates for individuals of
173 unknown sex (Efford, 2015). The impact of sex on both parameters g_0 and σ was tested through
174 the comparison of four alternative models using the Akaike Information Criterion, adjusted for
175 small sample size (AICc; Burnham & Anderson, 2002): “secc.0” (null model), “secc.sex.g0” (g_0
176 varies between males and females), “secc.sex.σ” (σ varies between males and females), and
177 “secc.sex” (both g_0 and σ vary between males and females) (Efford, 2015; Boron *et al.*, 2016).

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179 **RESULTS**

180 **Sampling effort & capture success**

181 A total sampling effort of 1,021 trap nights by 26 stations (mean trap nights per camera = 39.3)
182 yielded 57 leopard capture events. Of these, 31 (54%) were used to identify nine individual
183 leopards (five males, two females, two unsexed); the remaining 26 events (46%) were not suitable

184 for identification (due to picture quality and/or wrong flank) and therefore discarded. Capture
185 frequencies were 9, 3, 2, 2, and 1 for the five males; 6 and 4 for the two females; and 3 and 1 for
186 the two unsexed individuals.

187 **Density estimation**

188 The best SECR model (AICc=360.36) did not allow either g_0 or σ to vary with sex (secr.0), with
189 the model receiving significantly more support than the next best alternative (secr.sex. σ ,
190 $\Delta AICc=10.47$; Table 1).

191 The leopard density estimate of the best fitted model (secr.0) was $2.60 \pm SE 0.96$ adults per 100
192 km^2 . Capture probability at home range centre (g_0) was estimated at $0.043 \pm SE 0.013$, and the
193 scale parameter, σ , at $1,936 \pm 279$ m (Table 2). Buffer width stabilised at 10,000m, as reported by
194 similar leopard density studies (Gray & Prum, 2012; Borah *et al.*, 2013).

195 **Table 1 Here**

196 **Table 2 Here**

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198 **DISCUSSION**

199 **Leopard density**

200 Our study provides a baseline leopard density estimate for a relatively well-protected area of the
201 region, which is also the first empirical estimate for a leopard population in Mozambique. Using
202 SECR models, we estimated leopard density in XGR at 2.60 ± 0.96 adults per 100 km^2 . While
203 density estimates obtained in XGR are on the lower end of the spectrum relative to studies
204 elsewhere in sub-Saharan Africa, they are nonetheless higher than estimates from other protected
205 areas of southern Africa, including the densities of 0.60 leopards per 100 km^2 in the dry
206 savannahs of the Kalahari Gemsbok National park (South Africa; Bothma & Le Riche, 1984); of
207 0.62 per 100 km^2 in the savannah/woodland Cederberg Wilderness Area (South Africa; Martins

208 & Harris, 2013); and of 1.50/100 km² in the savannah habitat of the Kaudom Game Reserve,
209 Namibia (Stander *et al.*, 1997).

210 In South Africa's KNP, contiguous with XGR's western border, high leopard densities of
211 30.3/100 km² were reported for the Sabie riverine area (Bailey, 1993), and of 12.7/100 km² in the
212 N'wantesi concession (Maputla *et al.*, 2013). We believe the observed differences are most likely a
213 reflection of contrasting habitats, and consequently prey availability, between study sites. While
214 density estimates from KNP came from highly productive riverine forests (Bailey, 1993) and
215 savannah woodlands (Maputla *et al.*, 2013), XGR is predominantly comprised of nutrient-poor,
216 lower-productivity sandveld that is able to sustain lower animal densities (Redfern *et al.*, 2003;
217 Scholes *et al.*, 2003). Furthermore, the relatively high level of protection enjoyed by the reserve
218 (Andresen & Everatt, *unpublished data.*) indicate that artificially low prey densities due to human
219 hunting are unlikely.

220 Nonetheless, we cannot exclude the possibility that XGR could be acting as a population sink for
221 leopards dispersing from KNP, through anthropogenic mortalities occurring in the adjacent non-
222 protected areas (NPAs). While no estimates for anthropogenic leopard mortalities in the area are
223 available, it is possible that individuals venturing into the NPAs adjoining the reserve could be
224 suffering relatively high anthropogenic mortality rates, which in turn could attract leopards from
225 surrounding areas (*e.g.* KNP). This 'vacuum effect' has been documented in large carnivores and
226 in leopards in particular, and it may cause edge effects that affect the interior of even very large
227 protected areas (Loveridge *et al.*, 2007). Indeed, multiple incidents of poisoned leopards have
228 been recorded in nearby Limpopo National Park (Andresen & Everatt, *unpublished data.*) Longer
229 term camera trapping or GPS collaring efforts, combined with social surveys targeting the
230 communities outside the reserve, are necessary to ascertain whether this is the case.

231 **Methodological considerations and sex specific parameters**

232 The majority of our stations comprised only one camera-trap, rather than the two-camera set-up
233 (one for each flank) recommended (Karanth, 1995). Our strategy was a result of limited
234 resources, allowing us to survey a larger area and thus increase the number of captured
235 individuals. While we believe that in our case this was the best strategy, the trade-offs between
236 surveying a larger area and obtaining higher identification rates should be considered on a case-
237 by-case basis.

238 Interestingly, even though males commonly occupy territories overlapping with those of two to
239 four females (Bailey, 1993), more males ($n=5$) than females ($n=2$) were captured during our
240 study (although the gender of $n=2$ individuals could not be determined). Maputla *et al.* (2013)
241 also recorded a marked male-bias in capture rates, and cited several potential reasons for this, as
242 identified by Krebs (1999); heterogeneity in behaviour between genders in the vicinity of the
243 trap, and in tendencies to use trap locations (*e.g.* roads), were suggested as particularly probable
244 causes.

245 The SECR model which received the most support in the ranking was the model where sex did
246 not influence neither the detection (g_0) nor scale (σ) parameters. However, rather than indicating
247 the absence of widely described sex-dependent heterogeneity in behaviour and ranging patterns
248 (*e.g.* Bailey, 1993; Kittle *et al.*, 2017), we believe that the relatively small sample size did not
249 provide enough data to allow for the inference and modelling of sex-specific differences in
250 detectability and ranging patterns.

251 **Implications for conservation policy in Mozambique**

252 Trophy hunting has been shown to have substantial potential to foster conservation of large
253 carnivores (Lindsey *et al.*, 2007; Loveridge *et al.*, 2007), and it is estimated that each leopard
254 hunted in Mozambique has the potential to contribute in the region of \$ 24,000 to the local and
255 national economy (Jorge *et al.*, 2013). However, if poorly managed or additive to other source of
256 anthropogenic mortality, excessive harvesting of a species can reduce numbers to such an extent

257 that a population is no longer viable in the long term. Demonstrating that hunting practices,
258 including quotas, are biologically sustainable is therefore essential if trophy hunting is to be
259 considered an effective tool in the management and conservation of large African carnivores
260 ((Swanepoel *et al.*, 2014; Brackowski *et al.*, 2015).

261 Our results lead us to question the reliability of the estimates being employed to set leopard
262 quotas in Mozambique. The study by Martin & de Meulenaer (1988), quoted as the primary
263 justification for a recent trophy export quota increase in Mozambique (from 60 to 120
264 individuals per annum; CITES, 2007), states that up to 80% of Mozambique supports leopard at
265 between 3-10 individuals per 100 km². In addition, it also suggests that only 3% of the country's
266 total land area should exhibit leopard population densities lower than those found by the present
267 study. However, our estimated of 2.60 per 100 km² in XGR, one of the better protected areas in
268 the country, suggests that it is unlikely that many areas in Mozambique exhibit the densities cited
269 in the quota revision application. Although some landscapes will yield higher primary
270 productivity levels than XGR, it seems plausible that the high levels of anthropogenic
271 disturbances common in much of the country (Hatton *et al.*, 2001) would often more than
272 counteract this. Thus, while we appreciate that trophy hunting has not taken place in our study
273 area in almost 10 years (Andresen & Everatt, *unpublished data.*), and we acknowledge the
274 limitations of our study in terms of size and number of individuals encountered relative to the
275 overall range and total population, we believe that it is unlikely that leopard densities as high as
276 those cited in the quota increase application are common in the majority of areas where hunting
277 currently takes place.

278 As a result, we recommend further assessments of leopard population status and densities across
279 different habitats and land-use types across the country, in both hunting and potential protected
280 source areas. This would be an important first step towards the development of a sustainable and
281 empirical leopard trophy hunting quota allocation system in Mozambique, similar to that being

282 currently developed for neighbouring South Africa, which includes age-based hunting
283 regulations, adaptive management strategies, and dynamic, evidence-based quota systems
284 (Department of Environmental Affairs, 2017). Camera trapping surveys such as ours would be a
285 relatively rapid method to obtain robust estimates of leopard numbers at moderate cost (Balme *et*
286 *al.*, 2009), and, if followed by effective management interventions, would play an important role
287 in the species' successful recovery and conservation in many recuperating post-conflict
288 landscapes across the country.

289 Finally, we believe the identified conservation problems are not exclusive to Mozambique, with
290 both Tanzania and Namibia employing the Martin & de Meulenaer (1988) density estimates for
291 justification in previous leopard quota modifications approved by CITES (CITES 2002, 2004).
292 Our results reinforce the need for caution when setting leopard quotas, and the importance of
293 reliable population estimates across its range. We suggest similar research be carried out in other
294 regions where such estimates are used to set leopard harvest quotas, in the hope of a continent-
295 wide shift towards evidence-based processes being employed to guide management and policy.

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313

314 AUTHOR CONTRIBUTIONS

315 Data was collected by LA and KE; analyses were performed by PS; write-up was a collaboration
316 between all authors.

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446 TABLES

447 Table 1

Table 1 Model selection parameters for Spatially Explicit Capture Recapture (SECR) models in R package 'secr'

Model	AICc	Δ AICc	AIC wt	K	Dev.
g0 (.) sigma (.)	360.364	0.000	1	4	324.364
g0 (.) sigma (sex)	370.835	10.471	0	5	322.663
g0 (sex) sigma (.)	371.280	10.916	0	5	323.281
g0 (sex) sigma (sex)	394.663	34.299	0	6	322.835

AICc = Akaike Information Criterion, adjusted for small sample size; Δ AICc = difference in AICc values between each model and best ranking (lowest AIC) model; AICc wt = AICc model weights; K = number of model parameters; Dev. = Model deviances. g0 = probability of capture at home range centre; σ = spatial parameter related to home range size. secr.0: null model; secr.sex.g0: g0 varies between males and females; secr.sex: both g0 and σ vary between males and females; secr.sex. σ : σ varies between males and females.

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450 Table 2

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Table 2 Density and parameters estimated by the best Spatially Explicit Capture Recapture (SECR) model (secr.0)

	Value	SE	95% LCI	95% UCI
g0	0.043	0.013	0.024	0.078
Σ (m)	1963	279	1464	2562
D (N/100km²)	2.599	0.957	1.292	5.231

SE = Standard error; LCI and UCI = lower and upper confidence intervals respectively; D = Density. g0 = probability of capture at the home range centre; σ = spatial parameter related to home range size

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FIGURES

Figure 1

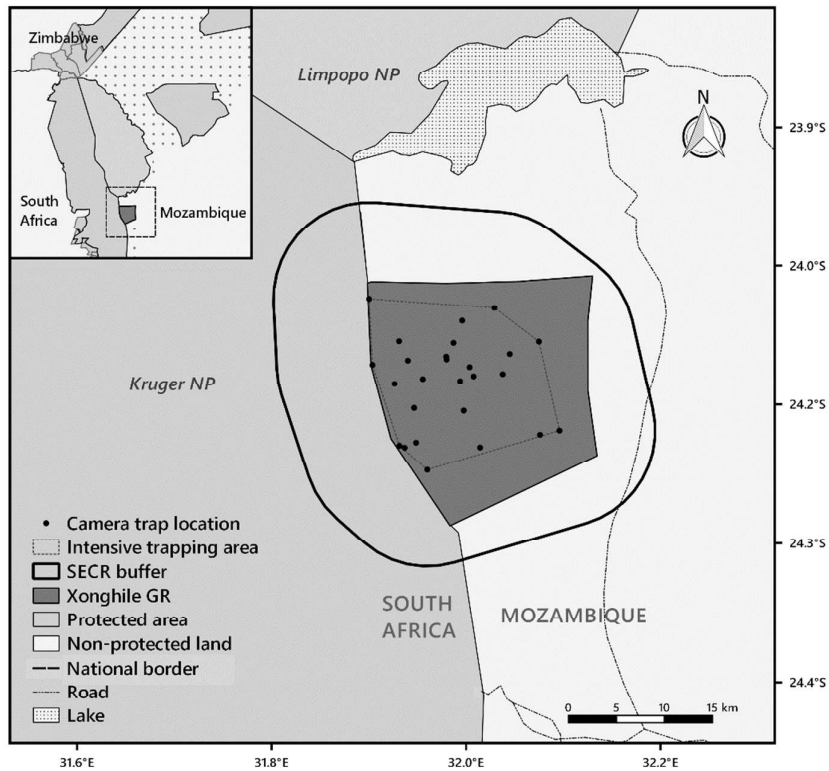


Figure 1 Legend

482 **Figure 1 Legend**
 483 **Fig.1** Xonghile Game Reserve (XGR), including camera locations and intensive trapping area within a
 484 10 km buffer zone, as required by the SECR models. Inset map: XGR in the context of the wider
 485 GLTFCA, comprising both protected areas (grey) and non-protected lands (dotted).

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