The mismatch between location of protected areas and suitable habitat for the Vulnerable taruka *Hippocamelus antisensis*

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Abstract Protected areas help to decrease human impacts on threatened mammals but do not always include species' core habitats. Here we focus on the Vulnerable taruka *Hippocamelus antisensis* near the Atacama Desert, Chile, a population that is mainly threatened by interactions with local human communities. We develop a species distribution model for taruka and assess the contribution of protected areas to safeguarding its preferred habitat. From sightings (collected during 2004–2015), absence records (collected in 2014), and environmental variables, we determined that taruka habitat is scarce, highly fragmented and limited to humid areas. Only 7.7–11.2% of the taruka's core habitat is under protection. We recommend the establishment of a protected area in the south of Arica-Parinacota district, an area without settlements that lies within the taruka's core habitat, along with educational programmes, fencing of crops, and inclusion of communities in decision-making in areas where farmer–taruka interactions are negative.

Keywords Chile, habitat suitability, *MaxEnt*, modelling, protected areas, spatial conservation planning, taruka, ungulate

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Protected areas help to decrease human impacts on habitat (Geldmann et al., 2013), one of the major causes of mammalian extinction (Ceballos & Ehrlich, 2002). Nevertheless, they do not always protect species' core habitats, often because the needs of threatened mammals are not easily met (e.g. species with large home ranges, or migratory habits; Berger, 2003), or because of planning and logistical shortcomings (e.g. scarcity of public land; Knight et al., 2011). Protecting core habitats is difficult when resources are scarce and in high demand by both humans and focal species (e.g. in arid regions humid areas are important for both native species and agricultural activities; Fritz et al., 2003). Coexistence between large mammals and humans can induce the former to move to areas where conflict may be high (Nyhus & Tilson, 2004) or cause them to be displaced to suboptimal locations (Verlinden, 1997).

Here we focus on the taruka *Hippocamelus antisensis*, categorized as Vulnerable on the IUCN Red List (Barrio et al., 2017), specifically the Chilean populations bordering the Atacama Desert. In this region the taruka is restricted to humid ravines (Barrio, 2013), which are exploited for agriculture (Fuentes-Allende et al., 2016). The southern extension of this population has contracted by 500 km northward since the arrival of Europeans in South America (Castro et al., 2004) and is now at a low density (Sielfeld & Guzman, 2011). This population is categorized as Critically Endangered (Cofré & Marquet, 1999) as a result of conservation threats mainly associated with interactions with local communities (Barrio, 2013). Although there are six protected areas within the taruka's range (Sielfeld & Guzman, 2011), it is not known whether these include ideal habitat for the species. We therefore identify core habitat types for the taruka and assess the contribution of protected areas in safeguarding these.

The study included 17,036 km² of Andean foothills (2,500–4,000 m altitude) in the Arica-Parinacota and Tarapacá districts in Chile (Fig. 1), 6,436 km² of which are included in the Chilean Protected Areas System (SNASPE, 2016; Supplementary Table 1). The area is dominated by canyons in which vegetation comprises mainly low scrub, with mean monthly temperatures of 0–18 °C and annual precipitation of 50–200 mm that mostly falls during December–March.

We developed a species distribution model, using *MaxEnt v. 3.3.3.k* (Phillips et al., 2006), to identify taruka habitat from sightings, absence records, and environmental variables, at a resolution of 1 km². From a total of 155 sightings obtained from the literature (Sielfeld & Guzman, 2011; Fuentes-Allende et al., 2016) and from an extensive study (BAG and NFA, unpubl. data) during 2004–2015, we selected 76 sightings (one per 1 km² grid cell, to reduce spatial autocorrelation and avoid pseudo-replication;

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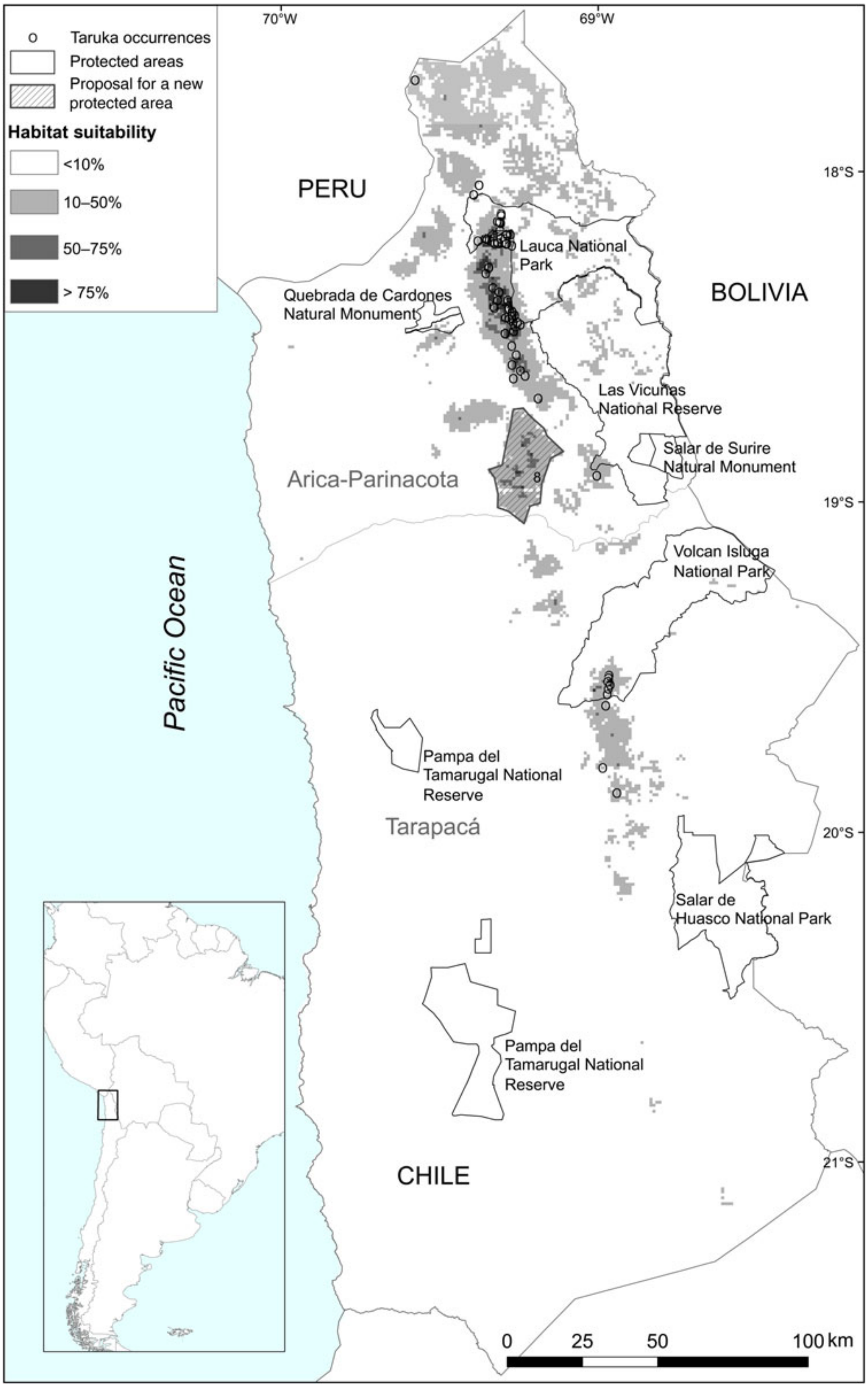

FIG. 1 Habitat suitability map for taruka *Hippocamelus antisensis* within the study area, with taruka occurrence and protected areas, including the proposed protected area (Supplementary Table 1).

Wellenreuther et al., 2012). Absence records (115 locations, one per 1 km² cell) were collected during the 2014 survey (Fuentes-Allende et al., 2016; Supplementary Material 1, Supplementary Fig. 1).

We initially chose 28 variables: topography (6 variables), climate (19 variables), normalized difference vegetation index (NDVI), and distance from each record to nearest ravine and nearest human settlement. Climatic variables with high auto-correlation were discarded ($R > 0.7$; Elith et al., 2006). Variables were then selected using boosted regression trees (Elith et al., 2008). Our final model was constructed via 4-fold cross-validation. Eight variables were selected that

TABLE 1 Environmental variables considered potential predictors of the distribution of the taruka *Hippocamelus antisensis*.

Variables	Abbreviation	Units/scale	Mean	Range		BRT[1] (%)
				Min.	Max.	
Topographic						
Mean altitude		m	3,647.60	2,450.29	4,671.51	**2.99**
SD of altitude			60.07	16.34	112.00	2.19
Mean gradient		%	30.98	11.33	46.03	**3.82**
SD of gradient			15.96	7.29	30.12	2.15
Mean roughness		%	25.35	12.53	35.88	2.09
SD of roughness			17.33	8.55	30.23	2.65
Location						
Distance to ravines		m	71,407.35	1.05	110,561.62	**24.6**
Distance to settlements		m	2,663.18	113.55	7,965.97	**5.28**
Climatic						
Annual mean temperature	Bio1*	°C	7.64	1.64	11.96	**3.49**
Mean diurnal range (mean of monthly (max. temp–min. temp))	Bio2		17.72	14.95	18.50	
Isothermality (Bio2/Bio7)	Bio3*	–	0.72	0.66	0.74	2.47
Temperature seasonality (SD)	Bio4*	°C	2.45	2.28	2.82	**7.67**
Max. temperature of warmest month	Bio5		18.80	12.74	22.66	
Min. temperature of coldest month	Bio6		−5.72	−12.27	0.00	
Temperature annual range (BIO5-BIO6)	Bio7		24.52	22.66	25.17	
Mean temperature of wettest quarter	Bio8		10.15	4.04	15.30	
Mean temperature of driest quarter	Bio9		5.23	−1.25	10.19	
Mean temperature of warmest quarter	Bio10		10.30	4.14	15.30	
Mean temperature of coldest quarter	Bio11		4.06	−1.85	7.99	
Annual precipitation	Bio12*	mm	189.87	39.31	292.14	2.42
Precipitation of wettest month	Bio13		80.19	15.03	99.31	
Precipitation of driest month	Bio14*		0.00	0.00	0.14	0.00
Precipitation seasonality (CV)	Bio15	%	160.47	137.79	172.47	**3.35**
Precipitation of wettest quarter	Bio16	mm	168.34	36.31	239.97	
Precipitation of driest quarter	Bio17*		0.71	0.00	3.29	0.62
Precipitation of warmest quarter	Bio18		159.26	36.31	221.80	
Precipitation of coldest quarter	Bio19*		1.11	0.00	4.29	2.07
Normalized Difference Vegetation Index	NDVI	(1–1)	0.20	0.05	0.35	**32.14**

*The climatic variables selected after excluding those with a correlation (R) > 0.7
[1]The relative contribution (%) of the predictor variables for a Boosted Regression Tree model (BRT) that determine taruka presence in northern Chile (Arica-Parinacota and Tarapacá districts; Fig. 1). Variables selected for constructing the distribution model are in bold.

best described the core habitat (Table 1; Supplementary Material 1).

The importance of each environmental variable in explaining taruka presence was assessed using Jackknife analysis and response curves of presence (Phillips, 2017). Model consistency was measured using the Area Under the Curve (AUC) index (Liu et al., 2005). We used logistic output format (Phillips & Dudik, 2008) to facilitate the interpretation of results, and determined areas where the species could occur using as cut-off thresholds the maximum value of the sensitivity–specificity sum (*MaxSS*; Jiménez-Valverde & Lobo, 2007) and the average value of all pixels included in the prediction (*Averprob*; Liu et al., 2005). Spatial overlap between potential distribution and location of protected areas was assessed using *ArcGIS 10.1* (ESRI, Redlands, USA).

The mean of the four models generated via cross-validation had good overall fit ($AUC_{mean} = 0.978 \pm SD$ 0.003). The relative importance of the selected variables' for predicted occurrence of the taruka were consistent for Jackknife and BRT analyses, confirming the robustness of our results (Tables 1 & 2). The model indicates that taruka core habitat is more abundant in Arica-Parinacota than in Tarapacá district (Supplementary Fig. 2). NDVI, distance to settlements, temperature, and seasonality of precipitation affected presence, but NDVI and distance to settlements had the greatest influence (Table 2; Supplementary Fig. 3a & d). High NDVI values (> 0.3), short distances to settlements, low thermal variation (Supplementary Fig. 3b) and high annual variation in precipitation (Supplementary Fig. 3c) increased the probability of taruka presence.

Food availability, inferred by NDVI (Pettorelli et al., 2005) and climatic variables, accounted for almost 60% of the probability of presence, reaching its maximum in areas with favourable conditions for plant growth (e.g. no pronounced

TABLE 2 Percentage contribution and relative predictive power of environmental variables in the MaxEnt habitat suitability model for taruka according to the MaxEnt Jackknife test. Training gains were calculated for a single variable if used solely for the modelling procedure and additionally for the model with the remaining variables after dropping the focus variable.

Variables	Contribution (%)	Jackknife test of training gain*	
		Only the variable	Without the variable
Topographic			
Mean altitude	6.17	0.75	2.72
Mean gradient	5.21	0.45	2.74
Location			
Distance to settlements	13.50	0.85	2.50
Distance to ravines	5.16	0.55	2.74
Climatic			
Bio1	6.08	0.78	2.72
Bio4	19.51	0.41	2.51
Bio15	18.95	0.51	2.78
NDVI	25.43	1.69	2.65
Total	100	2.81	

*Values are means of four Jackknife replicates of regularized training gain.

thermal variation or highly variable precipitation; O'Donnell & Ignizio, 2012), as suggested by other authors (Barrio, 2013; Fuentes-Allende et al., 2016). The physiology of the taruka limits the species to feeding on high quality vegetation (Müller et al., 2013; Gazzolo & Barrio, 2016), and thus it has a preference for the scarce productive areas confined to ravines. The influence of distance to settlements probably arises because in this region they are mainly confined to humid areas with high quality vegetation (Goykovic, 2012). Human settlements are scarce in the study area (one settlement per 48.2 km^2), but they are concentrated within the habitats favourable for taruka according to the Maxent model (one settlement per 11.7 km^2 in areas embraced by the *MaxSS* threshold), a coincidence that increases the likelihood of negative interactions with people. Damage to crops by taruka is common in Chile (Barrio, 2013).

The extent of the potential distribution of tarukas varied between the two cut-off thresholds (Supplementary Fig. 2). The *MaxSS* cut-off was 0.105, restricting the core distribution to 3,527.9 km^2 at altitudes of 2,500–4,500 m (394.9 km^2 within protected areas), and the *Averprob* cut-off was 0.562, restricting the core distribution to 304.1 km^2 at 3,000–3,500 m (23.5 km^2 within protected areas). Overall, the models suggest that taruka habitat is concentrated in the northern part of our study area over 2,500–4,000 m, with increasing fragmentation to the south.

Thus, there is a mismatch between taruka core habitat and protected areas, as for other deer species in Chile (e.g. 3–8% for pudú *Pudu puda*, Pavez-Fox & Estay, 2016; 30% for huemul *Hippocamelus bisulcus*; Quevedo et al., 2016). Much of the taruka's potential distribution lies in the pre-puna region, in which protected areas are scarce (Pliscoff & Fuentes-Castillo, 2011) and negative farmer–taruka interactions are common. The most suitable location for establishing a new conservation unit for taruka is in the south of the Arica-Parinacota district (Fig. 1) because this area offers a large expanse for protecting the pre-puna biodiversity (Rundel & Palma, 2000), there are no settled communities there, and protection of this area could help to prevent isolation of southern taruka populations. In the north and in areas where conflict occurs, other conservation approaches need to be considered, such as educational programmes to increase awareness about this deer species (Rechberger et al., 2014), and fencing of crops (VerCauteren et al., 2006) while still ensuring taruka have access to natural grasslands and watercourses (Hayward & Kerley, 2009), and consulting local communities prior to taking management decisions (Rechberger et al., 2014).

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Author contributions

NFA, BAG, AV and JEM: conceived and designed the study and performed the fieldwork. CM analysed the data and CM, NFA and JEM wrote the paper.

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Biographical sketches

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