

## Review

# Using an occupancy approach to identify poaching hotspots in protected areas in a seasonally dry tropical forest



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## ABSTRACT

Poaching activity has been described in the literature as harmful due to impacts on biodiversity, especially in protected areas. Although the main reason for this activity is subsistence, in many regions motivation goes beyond the limits of food necessity. We applied single-species, single season occupancy models to evaluate the spatial distribution of poachers and identify potential poaching hotspots in a mosaic of protected areas in the Caatinga domain, northeastern Brazil. We used camera-traps over a period of 200 days at 60 sites randomly selected. We used distances from human settlements, roads and the nearest water holes, frequency of game species and sampling effort as covariables that could influence poachers' occupancy and detectability and to identify potential poaching areas. Occupancy poachers were higher in sites with higher frequency of game species. Frequency of game species and distance from roads had a negative effect on the detectability of poachers. Spatial analysis indicated three critical poaching areas within and around the Boqueirão da Onça National Park, associated with roads and some isolated cattle and goat farms. In this study, we provided an assessment of poaching spatial patterns in relation to different landscape elements and biotic influences, indicating critical areas where enforcement efforts should be focused. Hotspots are clearly concentrated within and on the edge of National Park. The approach presented here to identify poaching hotspots is effective and economical, and therefore may be applied in other protected and non-protected areas throughout the world.

## 1. Introduction

Anthropogenic impacts' intensity on the environment is increasing, resulting in disproportionate biodiversity loss and ecosystem services collapse (Butchart et al., 2010; Laurance et al., 2012). Like habitat modification, poaching also represents a major threat to wildlife (Hoffmann et al., 2011; Dirzo et al., 2014). These multiple and increasing anthropogenic stressors result in cumulative effects with the potential to cause large-scale changes in ecosystems (Griffith et al., 2011), and make many species endangered (Beisiegel, 2017). Poaching, for example, is an activity that can negatively impact several populations of target species (Watson et al., 2013). The millionaire black market, especially in Asia, makes poaching effect on biodiversity even more dramatic. Even with international pressure to end illegal trade, thousands of animals are slaughtered annually, mainly in Africa, to supply the black market (Poaching Facts, 2020). In East Africa, for example, the elephant population has declined by almost 50% in recent

decades due to poaching (Simons, 2016). While in India, populations of tigers, leopards, Asian rhinos, and elephants are also suffering severe declines because of the market self-worth of their skins and ivories (Poaching Facts, 2020).

Poaching is a widespread activity in several parts of the world generating impacts that include population reductions or extirpation, additional capture of non-target species threatened with extinction and reducing ecological interactions in the communities (Peres, 2000; Becker et al., 2013; Sousa and Srbek-Araujo, 2017; Ferreguetti et al., 2019). Although in some context subsistence is the main reason for hunting, there are several other motivations that lead people to hunt wild animals (Bell et al., 2007). Hunting is an activity deeply rooted in cultural and social traditions (Castilho et al., 2017). In Brazil, poaching is widespread throughout the territory (Bragagnolo et al., 2019), but in the Brazilian semiarid region (Caatinga domain), this activity becomes even more dramatic. Given the adverse conditions of Caatinga, rural populations have developed a strong relationship and dependence on

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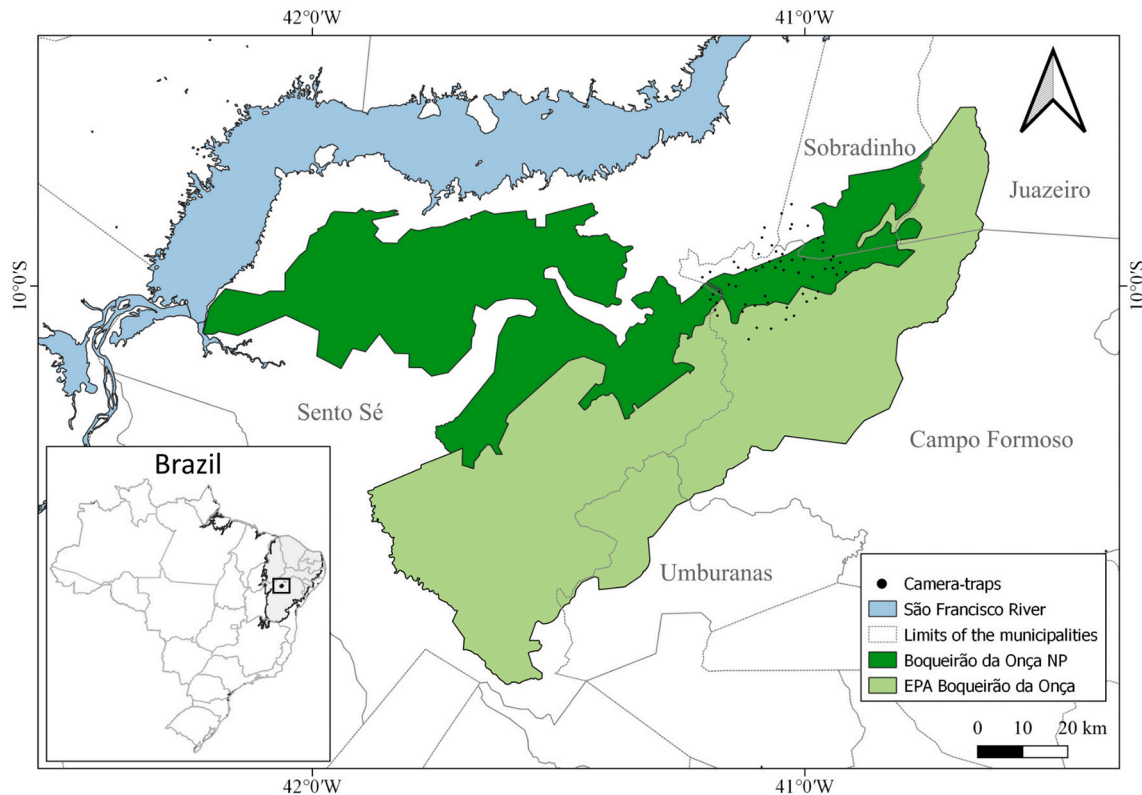


Fig. 1. Mosaic location of protected areas of Boqueirão da Onça, State of Bahia, northeastern Brazil. The Caatinga domain is shown in the insert (gray area).

natural resources, and poaching intensity is high and occurs since human occupation in the region, which has endangered the persistence and even caused local extinctions of some species (Alves et al., 2016). In the last decade, a wide scope of Ethnozoological study was produced for the Brazilian semi-arid region (Bezerra et al., 2011; Souza and Alves, 2014; Barbosa et al., 2018; Santos et al., 2019; Chaves et al., 2020). These studies demonstrated different uses of wild fauna by rural communities, which include food, medicinal use, religious rituals and pets.

In this context, wildlife harvesting can reach unsustainable levels due to increased human population and demand for wildlife, improved hunting techniques and increased access to natural environments (Castilho et al., 2017). Caatinga's rapid and continuous large-scale advancement of infrastructure, especially wind farms, has significantly increased access and facilitated poaching activities in several previously remote regions (Dias et al., 2019). Similar scenarios have been observed in the forests of the Congo, where the establishment of logging companies has resulted in the expansion of roads and consequently boosted poaching and illegal bushmeat trade (Wilkie et al., 2000). In Brazil, hunting has been banned for over 50 years by the Wildlife Protection Act (Federal Law 5197/1967) and ratified by the Environmental Crime Law (Federal Law 9605/1998) and is permitted only for subsistence purposes on indigenous lands and in extremely poor rural areas. Those who break the law are subject to detention from six months to one year, and a fine (art. 29 Federal Law 9605/98).

Although penalties be tripled for poaching within protected areas and for the killing of endangered species (art. 29 Federal Law 9605/98), unfortunately poaching in Brazil occurs intensely, even in protected areas (Sousa and Srbek-Araujo, 2017). This is partly because these protected areas are insufficiently managed due to the lack of human, financial and infrastructure resources to monitor and combat poaching (Peres and Lake, 2003; Ferregueti et al., 2018). In addition, a quantitative metric is lacking to effectively assess the impact of poaching across the Neotropical region (Ferregueti et al., 2019). Therefore, given the critical need for effective allocation of limited resources to

combat environmental crime, understanding spatial and temporal patterns of poaching is an essential component of focusing conservation efforts on protected areas (Watson et al., 2013).

In this scenario, combating poaching is a challenge worldwide, given that efforts against this illegal practice are always underfunded and with few resources. In this study, we combined occupancy models and heat map technique to identify where hunting activities occur most intensely in protected areas of an endemic ecosystem of Brazil. With our distribution models, we aimed to illustrate areas with a high probability of poaching and help environmental agents to allocate their limited resources in these areas. Our general hypothesis was that poaching spatial distribution and intensity is higher in sites with greater accessibility. We then predicted that the probability of poachers' occupancy and detection would be higher at sites closer to human settlements and roads. Considering that water is a limiting and scarce resource in the Caatinga domain, we expected to find a negative correlation between the likelihood of occupancy and detection of poachers and the distance to permanent water holes. We also predicted that poachers' occupancy and detection would be higher at locations with higher frequency of game species.

## 2. Material and methods

### 2.1. Study area

The Boqueirão da Onça region is inserted in the Seasonally Dry Tropical Forest (Caatinga domain) and is considered the largest continuum of this genuinely Brazilian phytophysiognomy. Boqueirão da Onça consists of a mosaic of protected areas formed by the Boqueirão da Onça National Park (NP) (3469 km<sup>2</sup>) and Boqueirão da Onça Environmental Protection Area (EPA) (5057 km<sup>2</sup>). These protected areas extend for five municipalities in the state of Bahia, northeastern Brazil (Fig. 1). In Brazil, protected areas are called Conservation Units and are classified into two groups: Integral Protection Units and

**Table 1**

Covariates used to model the probabilities of occupancy ( $\Psi$ ) and detection ( $p$ ) of poachers at Boqueirão da Onça mosaic, Bahia, northeastern Brazil. The mean (range) of values are given for each covariate.

Covariates	Mean and range (minimum–maximum)
Distance from settlements (km)	9.66 (0.70–16.30)
Distance from roads (km)	2.22 (0.01–6.72)
Distance from water holes (km)	5.07 (0.22–15.60)
Frequency of game species	0.15 (0.00–0.90)
Days of camera operation	144.6 (30–200)

Sustainable Use Units. PN is an Integral Protection Conservation Unit and has as its primary objective the preservation of natural ecosystems of great ecological relevance and scenic beauty. Scientific research, education and environmental interpretation, recreation and ecotourism activities are under restrictions and rules established by the agencies responsible for its administration (Brasil, 2006). EPA is a more permissive protected area category than NP. In general, the EPA has a large area, consisting of public and private lands, where some economic activities can be carried out in compliance with rules established by the Conservation Units management body (Brazil, 2006).

In this region, the rainy season is short and unpredictable, but usually extends from October to December. Precipitation and average annual temperature during the study were 563.6 mm and 27 °C, respectively (INMET, 2018). The phytophysognomy is xerophilous and deciduous composed by the arboreal-shrubby caatinga and the arboreal caatinga, predominant vegetation types in this ecoregion (Velloso et al., 2002). However, other environments form a mosaic of phytophysognomies, including open areas of shrubby caatinga, rock fields, plateau vegetation and stands of palms, known as veredas. Areas of more denser vegetation with emergent trees can be found in scarps and deep valleys (Dias et al., 2019). As in most regions of the Brazilian semi-arid region, most streams are ephemeral and the few sources of water that last longer during the dry season are available in some wells or holes.

## 2.2. Camera-traps

We conducted a camera-traps study over a period of 200 days (between January and July 2017), during the dry season, to model the probability of poachers' occupancy and detection and their spatial distribution in Boqueirão da Onça mosaic. We established a grid of 20 × 30 km (600 km<sup>2</sup>) over the digital map of the study area, which was subdivided into 150 plots of 4 km<sup>2</sup> each. We randomized 60 plots to establish the sampling sites. At each site, we installed a camera-traps, and the average distance between traps was 2 km (range 1.5 km–3.28 km). The 60 traps were permanently active at the same sites during the 200 days of the survey and we set them to operate for 24 h. We installed the equipment primarily on unpaved trails and roads, approximately 40 cm above ground level. To calculate sampling effort, we excluded the traps that were stolen ( $n = 2$ ) and the days on which the cameras were nonoperational. In the latter case, the day on which the last record was obtained was considered to be the last day on which the camera was operational for the calculation of sampling effort. We classified as poachers all photographed individuals carrying a gun and/or some slaughtered animals (see Ferregueti et al., 2018).

## 2.3. Occupancy modeling

Occupancy probability ( $\Psi$ ) is defined as the probability of site  $i$  being occupied by the species, while detection probability ( $p$ ) is defined as the probability of detecting the species at site  $i$  at time  $t$ , conditional on site being occupied by the species. These parameters can be modeled in function of covariates (MacKenzie et al., 2002). The probability of

detection may vary spatially due to habitat characteristics, or temporarily due to seasonal fluctuations in behavioral patterns and environmental conditions (Bailey et al., 2004). In this context, we interpreted the probability of detection as the intensity (or frequency) of use (Cassano et al., 2017).

To explore occupancy probability ( $\Psi$ ) of poachers in Boqueirão da Onça we measured two accessibility covariates at each sampling site. Specifically, at each site, we measured the distances (km) from human settlements (farm headquarters and villages) and nearest unpaved roads (built by wind power company). As water is a limiting resource in Caatinga, we also measured the distance from the nearest permanent water holes known (e.g. natural wells and lagoons). All distance covariates (settlements, roads, and water holes) were calculated as a straight line (Euclidean distances) using QGIS software (QGIS Development Team, 2017). Additionally, we selected eight commonly hunted species based on previous studies on hunting strategies and key hunting species in Caatinga (Alves, 2009; Alves et al., 2016). The selected game species were: *Tamandua tetradactyla*, *Dasyus novemcinctus*, *Euphractus sexcinctus*, *Tolypeutes tricinctus*, *Mazama gouazoubira*, *Pecari tajacu*, *Kerodon rupestris* and *Dasyprocta nigriclunis*. We summed the total records of species obtained for each site and divided by the sample effort expended at each site, thus obtaining a frequency index of species recorded (Table 1). We considered species-independent records only those obtained at intervals  $\geq 1$  h at each site. We also used distance covariates for settlements, roads, nearest water holes, and the frequency of game species to model the detection probability ( $p$ ) of poachers. Finally, we considered the number of days each camera was operating at each site and sampling occasion to test covariate effect on poachers' detection (Table 1).

## 2.4. Data analysis

We used the single-season occupancy model (MacKenzie et al., 2002) to determine the influence of covariates on poachers' occupancy probability and detection in the Mark program (White and Burnham, 1999). We grouped the 200 sampling days in 10 occasions of 20 days, in order to compose a detection history of poachers in sampling sites. As our main objective was to select predictor covariates with a higher effect on the occupancy probability and detection of poachers, we adopted the model selection strategy based on all possible combinations of all measured covariates. Specifically, we build models from all possible additive combinations for covariates that could influence the probability of poachers' occupancy ( $\Psi$ ) and detection ( $p$ ). This strategy resulted in a set of balanced models (Doherty et al., 2012), which allowed us to calculate the cumulative weight of AICc ( $w_+$ ) of each covariate (Burnham and Anderson, 2002) and to evaluate the most likely ones ( $w_+ \geq 0.50$ ) to influence the occupancy and detection of poachers. We tested for possible overdispersion (i.e. c-hat), which can be interpreted as lack of independence between sites using the goodness-of-fit test developed specifically for single-season occupancy analysis (MacKenzie and Bailey, 2004) analyzed in the PRESENCE software (Hines, 2006).

We used the best fitted occupancy model (model with lowest AICc) to plot the spatial distribution of poachers in the study area, using estimates of model-specific coefficients and covariate information that best represented poachers' occupancy ( $\Psi$  (Game<sub>sp</sub>),  $p$  (Water + Roads + Game<sub>sp</sub>)) for each sample site (i.e. camera-traps). Occupancy estimates included in the best fitted model incorporated imperfect detection and resulted in a map of the predicted occurrence of poachers in the study region. Then, we apply the heat map technique to identify poaching hotspots in our study area (Rosenblatt, 1956; Parzen, 1962). The heat map enables rapid identification of critical points by weighing poacher's detectability in the study area. We built this map using QGIS (QGIS Development Team, 2017) with the Heat Map plugin using the regular grid centroids as input to the occupancy model estimates.

**Table 2**

Top 20 best fitted models used to model the probabilities of occupancy ( $\Psi$ ) and detection ( $p$ ) of the poachers at Boqueirão da Onça, Bahia, in northeastern Brazil. The  $\Psi$  values are modeled based on the distance from settlements (Sett), roads, water holes (Water) and frequency of game species (Game<sub>sp</sub>). The  $p$  values are modeled as a function of the same previous covariates with addition of the number of days in which the cameras were operational (Cam).

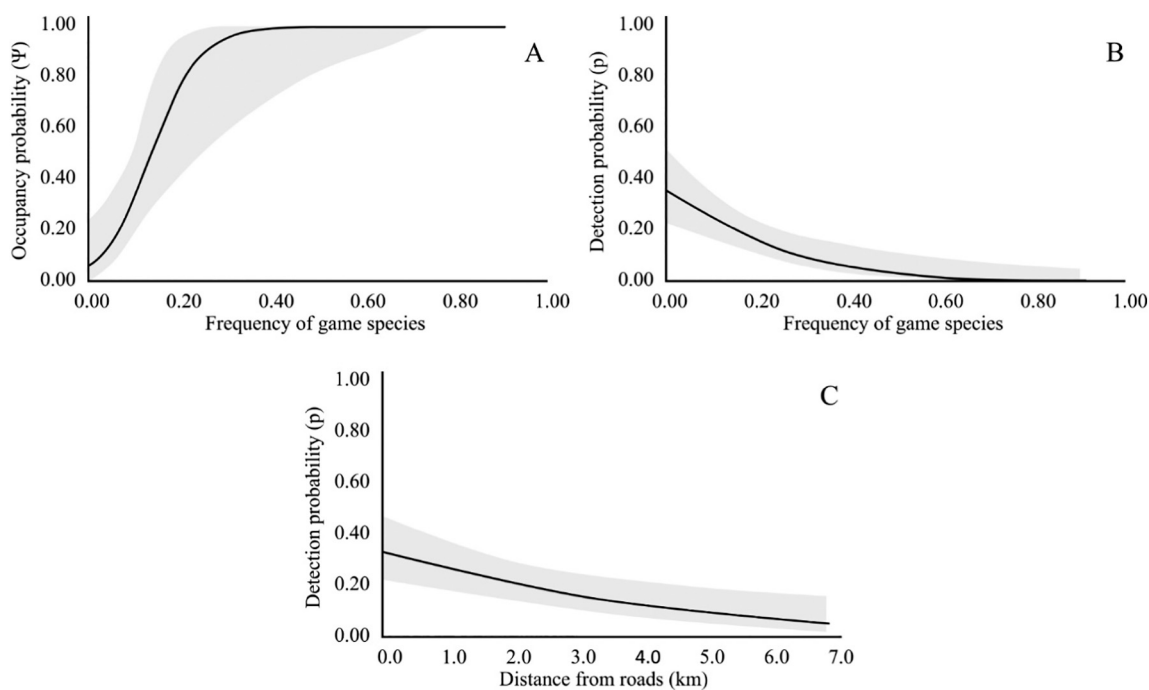
Models <sup>a</sup>	AICc	ΔAICc	AICcw	Number of parameters	Deviance
$\Psi$ (Game <sub>sp</sub> ) $p$ (Water + Roads + Game <sub>sp</sub> )	222.91	0.00	0.19	6	209.32
$\Psi$ (Game <sub>sp</sub> ) $p$ (Roads + Game <sub>sp</sub> + Cam)	223.14	0.23	0.17	6	209.56
$\Psi$ (Game <sub>sp</sub> ) $p$ (Roads + Game <sub>sp</sub> )	223.17	0.26	0.17	5	212.06
$\Psi$ (Roads + Game <sub>sp</sub> ) $p$ (Roads + Game <sub>sp</sub> )	224.01	1.10	0.11	6	210.42
$\Psi$ (Game <sub>sp</sub> ) $p$ (Sett + Roads + Game <sub>sp</sub> )	224.33	1.42	0.09	6	210.75
$\Psi$ (Water + Game <sub>sp</sub> ) $p$ (Roads + Game <sub>sp</sub> )	224.96	2.05	0.07	6	211.37
$\Psi$ (Sett + Game <sub>sp</sub> ) $p$ (Roads + Game <sub>sp</sub> )	225.01	2.10	0.07	6	211.42
$\Psi$ (Game <sub>sp</sub> ) $p$ (Water + Sett + Game <sub>sp</sub> )	226.06	3.16	0.04	6	212.48
$\Psi$ (Water + Sett + Roads + Game <sub>sp</sub> ) $p$ (Water + Sett + Roads + Game <sub>sp</sub> + Cam)	228.65	5.74	0.01	11	201.15
$\Psi$ (Game <sub>sp</sub> ) $p$ (Water + Game <sub>sp</sub> + Cam)	229.06	6.16	0.01	6	215.48
$\Psi$ (Game <sub>sp</sub> ) $p$ (Water + Game <sub>sp</sub> )	230.48	7.58	0.00	5	219.37
$\Psi$ (.) $p$ (Water + Roads + Game <sub>sp</sub> + Cam)	230.48	7.58	0.00	6	216.90
$\Psi$ (.) $p$ (Sett + Roads + Game <sub>sp</sub> + Cam)	231.80	8.90	0.00	6	218.22
$\Psi$ (.) $p$ (Roads + Game <sub>sp</sub> + Cam)	231.99	9.08	0.00	5	220.88
$\Psi$ (.) $p$ (Roads + Game <sub>sp</sub> )	232.02	9.12	0.00	4	223.30
$\Psi$ (.) $p$ (Water + Sett + Wind + Cam)	232.20	9.30	0.00	6	218.62
$\Psi$ (Water + Game <sub>sp</sub> ) $p$ (Water + Game <sub>sp</sub> )	232.21	9.30	0.00	5	221.10
$\Psi$ (.) $p$ (Water + Roads + Cam)	232.23	9.32	0.00	6	218.64
$\Psi$ (Sett + Game <sub>sp</sub> ) $p$ (Water + Game <sub>sp</sub> )	232.28	9.37	0.00	6	218.70
$\Psi$ (Roads + Game <sub>sp</sub> ) $p$ (Water + Game <sub>sp</sub> )	232.62	9.71	0.00	5	221.51

<sup>a</sup> The plus (+) signal means an additive effect between two or more covariates and the dot (.) means no covariate effect on both parameters.

**3. Results**

Our study resulted in a sampling effort of 8678 trap-days with 1345 independent records of game species and 77 records of poachers. We recorded poachers at 15 of the 60 sampling sites. The goodness-of-fit test did not indicate overdispersion in our dataset ( $\hat{c} = 0.7$ ;  $p = 0.73$ ). We built 257 models from all possible additive combinations for covariates that could influence the probability of poachers' occupancy ( $\Psi$ ) and detection ( $p$ ) (Table 2). The frequency of game species positively influenced poachers' occupancy probability in Boqueirão da Onça (Fig. 2A; Table 3). The distance from human settlements, roads and

water holes did not influenced the poaching occupancy probability ( $w_+ < 0.50$ ; Table 3). The frequency of game species and the distance from roads showed a negatively effect on poachers' detection probability (Fig. 2B and C, respectively). While distances from human settlements, water holes and sampling effort did not influence poachers' detection probabilities ( $w_+ < 0.50$ ; Table 3). The resulting map from our estimates showed that poaching activity's spatial distribution varies consistently across the Boqueirão da Onça protected area, with more frequency at three specific points (hotspots) that are near to farm headquarters and roads (Fig. 3).



**Fig. 2.** Probability of poacher's occupancy (+95% CI) as a function of frequency of game species (A). Poachers detection probability (+95% CI) as a function of frequency of game species (B) or distance from roads (C) at occupied sites. Estimates are from the most parsimonious model that included those covariates,  $\Psi$  (frequency of game species), and  $p$  (frequency of game species and distance from roads).



**Table 3**

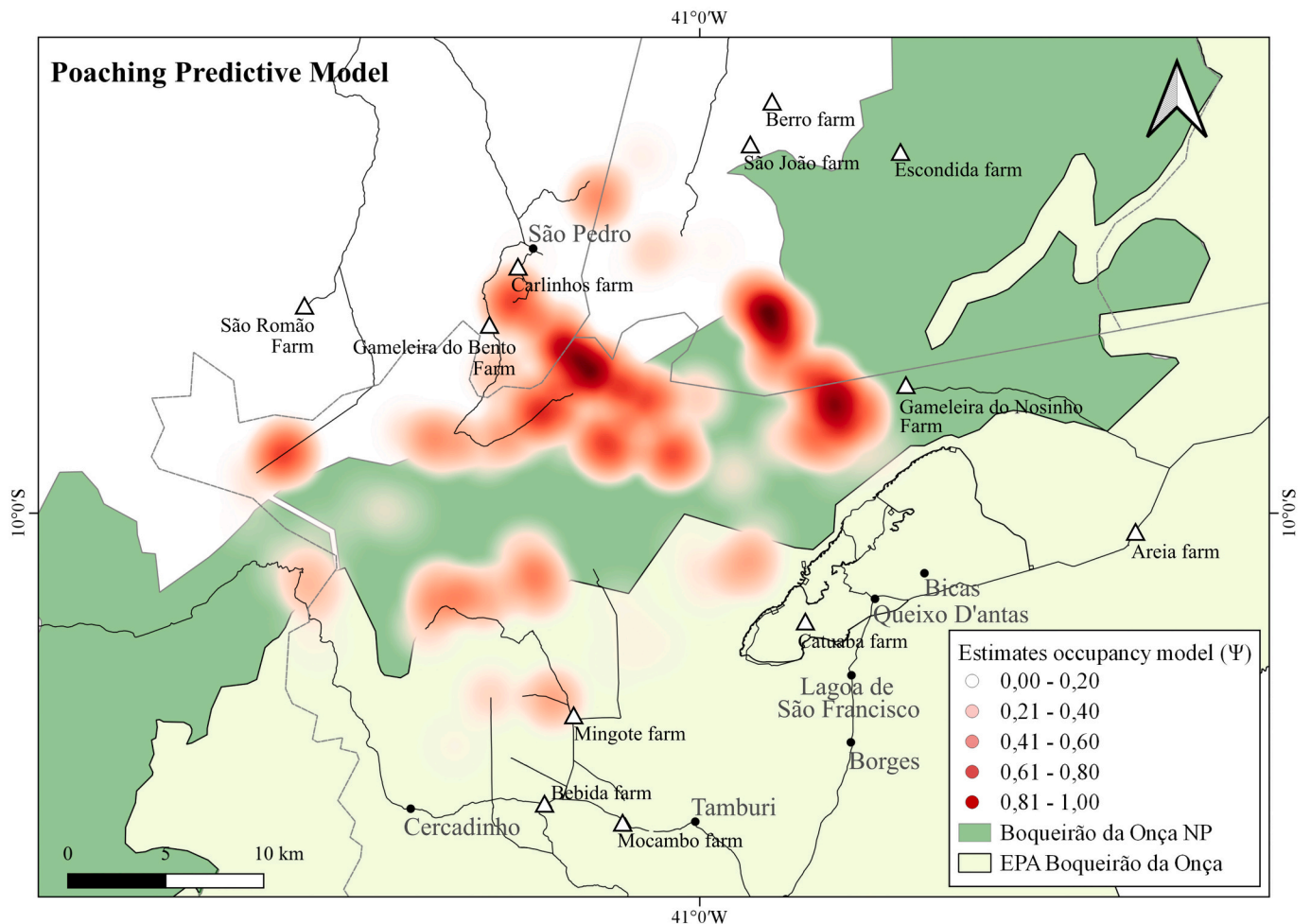
Cumulative AICc weights for the covariates used to model the occupancy probabilities ( $\Psi$ ) and detection ( $p$ ) of poachers at Boqueirão da Onça, Bahia, northeastern Brazil. The estimates of the effects of the covariates ( $\beta$  parameters) are given for the most parsimonious model that included each covariate. The  $\Psi$  values are modeled based on the distance from settlements, roads, water holes and frequency of game species. The  $p$  values are modeled as a function of the same previous covariates with addition of the number of days in which the cameras were operational. The mean values of occupancy ( $\bar{\Psi}$ ) and detection ( $\bar{p}$ ) of the species were obtained from the most parsimonious models, which included the covariates with the highest cumulative weight ( $w_+ \geq 0.50$ ).

Covariates	Cumulative AICc weights	$\beta$ parameters			Real parameters		
		Estimate	Lower 95% IC	Upper 95% IC	Estimate	Lower 95% IC	Upper 95% IC
<b>Poachers occupancy (<math>\Psi</math>)</b>							
Frequency of game species	0.93	19.22	6.01	32.42	-	-	-
Distance from roads	0.12	0.30	-0.20	0.81	-	-	-
Distance from water holes	0.09	-0.11	-0.37	0.15	-	-	-
Distance from settlements	0.08	-0.09	-0.34	0.14	-	-	-
$\bar{\Psi}$	-	-	-	-	0.41	0.27	0.55
<b>Poachers detection (<math>p</math>)</b>							
Frequency of game species	0.96	-5.27	-8.29	-2.24	-	-	-
Distance from roads	0.90	-0.31	-0.51	-0.11	-	-	-
Distance from water holes	0.28	0.09	-0.01	0.20	-	-	-
Camera operation	0.22	0.05	-0.01	0.11	-	-	-
Distance from settlements	0.15	0.07	-0.05	0.19	-	-	-
$\bar{p}$	-	-	-	-	0.10	0.05	0.15

**4. Discussion**

Our study was carried out in the largest *continuum* of Seasonally Dry Tropical Forest in Brazil, a representative area and considered a high priority for conservation. We showed that occupancy modeling can be a

useful tool to identify areas with a higher incidence of poaching in protected areas, using different covariables that can influence the occupancy and detectability of poachers. Our findings indicated that distance to roads and frequency of game species were the best-fitted covariates to estimate poaching distribution in the protected areas of



**Fig. 3.** Map with occupancy rates using the best fitted model ( $\Psi$  (Game<sub>sp</sub>)  $p$  (Water + Roads + Game<sub>sp</sub>)) which predicted the spatial distribution of poachers for the Boqueirão da Onça protected areas mosaic. Black dots indicate the villages.

Boqueirão da Onça. These predictive models can help environmental managers to identify and combat these illegal activities.

Among our accessibility covariates, the distance from roads was the only that influenced the spatial distribution of poachers. Our findings reflected a strong influence of roads on poacher's detectability. Similar relationships were observed in other regions of Brazil and around the world (Wilkie et al., 2000; Barboza et al., 2016), where the spatial distribution of poaching occurrence and intensity was highly correlated with accessibility. Roads are considered strong predictors of poaching as they act as access routes between settlements and favorite hunting grounds (Watson et al., 2013). In Caatinga, poachers increasingly use roads to access areas deemed most suitable for poaching (Barboza et al., 2016). Economic development is particularly important for human societies, especially in less favored areas, such as the Brazilian semiarid region. The establishment of wind farms in various locations in Caatinga has somewhat changed this landscape, providing employment and income for several families in rural communities. However, these large infrastructures have been of concern to conservation biologists operating in the region (Dias et al., 2019). Although wind power is an important source of renewable energy, it also causes environmental impacts (Costa et al., 2017). In this sense, expansion plans of wind power sector has overlapped the areas considered of high importance for the conservation of biodiversity in Caatinga (Neri et al., 2019). In addition, the establishment of several wind farms in Boqueirão da Onça resulted in the exponential increase of new roads and other accesses in areas previously considered remote (Dias et al., 2019). These new accesses have benefited poachers, who can travel ever higher distances by motor vehicles. As observed elsewhere, vehicles continued use associated with trained dogs and firearms has increased pressure on wildlife populations and, consequently, concerns about species conservation (Barboza et al., 2016).

We did not identify the influence of distance to water holes on the distribution of poaching. We believe that this result may be related to the hunting technique used in our study area. In Boqueirão da Onça, as in other locations in the Caatinga, poachers generally use active search with the cooperation of trained dogs, especially to hunt mammals (Alves, 2009; Dias et al., 2019). Ambush hunting near water holes is most often carried out with the aim of catching birds (Alves, 2009). Thus, the distribution of poaching aimed at mammals does not seem to depend on the water availability.

Our results indicated that frequency of game species was the only covariate that positively influenced poachers' occupancy probability in Boqueirão da Onça. This positive effect of frequency of game species in poachers' occupancy, suggests that the distribution of poaching is higher in areas of greatest abundance of game species. As noted by Ferreguetti et al. (2018), poachers prefer areas where they know that some preferred mammal species are found more often, thereby increasing the cost-effectiveness of poaching expeditions. This also reflects the influence of habitat type, as more preserved environments harbor high mammal diversity and abundance, including endangered species (Barboza et al., 2016). It is important to consider that the game species evaluated in this study are widely poached throughout the Caatinga domain, highlighting the preference for this group of mammals by poachers in this region of Brazil (Alves et al., 2016). Mammalian poaching in Caatinga has already proved unsustainable, as local extinctions and population declines of *Mazama gouazoubira*, *Pecari tajacu* and *Tolypeutes tricinctus* have been documented (Alves et al., 2016; Barboza et al., 2016). Not surprisingly, these game species are classified at some level of concern for conservation, especially in the state of Bahia (Campos et al., 2019). Contrary to our expectations, poachers' detection probability was negatively affected by the frequency of prey species. Although most occupied sites by poachers are those with the greatest frequency of game species, the intensity of use of these sites by poachers did not follow this pattern. This result indicates that the poaching pressure in Boqueirão da Onça is not homogeneous, it concentrates in some specific locations forming the most intense poaching hotspots.

Our spatial analysis corroborates this effect, indicating three critical areas, two in Boqueirão da Onça NP in the Gameleira do Noinho farm area and one in the outer edge of the protected area, in an area close to the Gameleira do Bento farm. These findings may be related to the proximity to the headquarters of these farms. In southeastern Brazil, poaching intensity is related to proximity to human settlements, which favors access to natural habitats (Ferreguetti et al., 2018). During our fieldwork, we obtained various evidence of poaching in all areas visited, most often being observed on the Gameleira do Noinho and Gameleira do Bento farms. In these farms we observed wild animal carcasses, hunting dogs, firearm sounds and the presence of the poachers themselves, who usually gather in these places on weekends, from where they depart for poaching in the native vegetation. It is notable that both game species abundance and accessibility are attractive to poachers, which increases poaching pressure on wild species (Wilkie et al., 2000; Ferreguetti et al., 2018).

In Brazil hunting is prohibited by law (Federal Law 9605/1998) and is only allowed on a subsistence basis in indigenous lands and extremely poor rural areas. However, while poverty is a motivator for hunting in rural communities, this activity transcends socioeconomic needs (Bell et al., 2007). In the past two decades, for example, large federally funded social programs were introduced in Brazil, with the aim of reducing poverty (Bragagnolo et al., 2019). In addition, studies show that poachers spend resources on poaching expeditions, including fuel for vehicles, weapons, and ammunition, which invalidates the argument of the need to hunt for food (El Bizri et al., 2015; Barboza et al., 2016). Thus, poaching in Caatinga is more a matter of leisure and taste for wild meat than a food necessity (Barboza et al., 2016). However, with the emergence and worsening of the COVID-19 pandemic in the world, there is a fear of an increase in poaching in rural communities (Briggs, 2020). The relationship stems from the economic impact and loss of income of societies in the face of the pandemic (McKibbin and Fernando, 2020). This is very worrying, especially in regions with a low human development index (HDI) such as the municipalities that make up Boqueirão da Onça, who's average HDI is 0.59 (IBGE, 2010). In this sense, with the imminence of increased pressure from poaching on legally protected species in times of global economic crisis, becomes an even greater challenge to curb criminal practices against wildlife.

It is also important to note that the impunity feeling motivates many people to practice poaching in Brazil. In part, because law enforcement in many regions is irregular, infrequent, or even non-existent due to lack of human and financial resources (Castilho et al., 2017). The inefficiency of Brazilian environmental surveillance agencies is further compounded by the planning of protected areas. At the landscape level, poorly planned reserves may include, among other factors, a biased outline of the original boundaries, where crucial habitats are left unprotected (Peres and Lake, 2003). An example of this is the mosaic of protected areas of Boqueirão da Onça, where the proposal to create the National Park lasted 16 years. Successive changes due to different land use and occupation interests in the region culminated in the creation of a mosaic of different types of protected areas, with a reduction of > 50% in the area of the National Park, originally proposed (Campos et al., 2019). In addition, Brazilian law provides that private areas within the boundaries of National Parks will be expropriated (Brasil, 2006). Unfortunately, these expropriation processes take many years to complete, while impacts continue to occur within the reserves as noted in Boqueirão da Onça. Thus, reducing poaching in protected areas in Brazil is challenging and complex, requiring an integrated approach focused on mapping the most critical areas that depend on more conservation efforts.

Poaching is an activity strongly rooted in the Brazilian semi-arid region, and this relationship between humans and biological resources is strongly linked to cultural and socioeconomic conditions (Silva et al., 2019). Several ethno-zoological studies have outlined an overview of hunting techniques used in the Caatinga, as well as the preferred species and main uses (Bragagnolo et al., 2019; Chaves et al., 2020). In this

way, the knowledge about the behavior of poachers combined with the results that we present here, can help in understanding about the impacts of poaching on wildlife. Our study has shown that poaching occurs within and around the mosaic of protected areas of Boqueirão da Onça, northern Bahia. We provide here an assessment of the spatial patterns of poaching in relation to different landscape elements and biotic influences, allowing clear predictions of where poaching hotspots occur in the landscape and where enforcement efforts should be focused. Hotspots are clearly concentrated inland and on the edge of Boqueirão da Onça NP and are associated with roads and some farms. To achieve conservation objectives, we suggest that environmental agencies and Boqueirão da Onça managers should limit road expansion and expropriate settlements within the National Park. Patrols must also be carried out at the borders of protected areas to combat not only hunting but also deforestation and burning. However, the current scenario is daunting, as Brazilian environmental policy has suffered serial setbacks. State environmental agencies have been delegitimized and their actions limited by the federal government itself. Additionally, a law project is being debated in the Brazilian Congress (PL 6268/2016) aimed at repealing the fauna protection law (Law No. 5.197, 1967), thus allowing hunting and killing of wild animals in the national territory, if approved by congresspeople. Given this bleak panorama, it has never been so urgent to do conservation in Brazil.

#### Declaration of competing interest

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

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