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Hoary fox habitat selection opens livestock grazing management opportunities to combine cattle production and carnivore conservation

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Dedico a todas as vidas com que sonhei

e àquelas com as quais caminhei, somos um.

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Índice

Abstract

Pasture expansion raises the challenge of improving livestock production while conserving wildlife. Livestock Grazing Management (LGM) is usually designed to boost production, but its relationship with wildlife is little known. Sward surface height (SSH) represents the vegetation structure available to cattle and wildlife. Using SSH as a proxy of LGM, we aim to suggest a management that benefits cattle beef production and conservation of a vulnerable mammal, the hoary fox (*Lycalopex vetulus*). To do this, we evaluated fox habitat selection in pasturelands under different SSHs of cattle beef private farms on Brazilian savanna. We radio-tracked thirty foxes over ten years and applied Resource Selection Functions to estimate their habitat selection under two biological orders (home-range and within home-range) in two habitat scales (coarse- and fine-grained). For coarse-grained habitats, foxes selected pasture over woodland on both biological orders, as expected due to being a species specialized in open areas. For fine-grained habitats within their home ranges, both sexes selected medium SSH during the day, and females selected low SSH at night. Foxes selected maize crops to feed on insects, and medium and low SSHs to forage, rest, and breed. Our results suggest pro-hoary fox management that can be applied on natural habitats already converted to pastures and reconcile farmers and foxes. Pro-hoary fox management includes a LGM with moderate grazing pressure under a rotational system (providing low and medium SSH) and integrating pasture with small maize crops. This pro-hoary fox management can align improved livestock production with hoary fox conservation.

Keywords: Wildlife conservation; movement ecology; Cerrado; land-use change; agroecosystem; farm management.

Resumo

A expansão da pastagem sobre os habitats naturais levanta a questão de como podemos melhorar a produção de gado e ao mesmo tempo conservar os animais silvestres. O manejo de pastagem (MP) é geralmente aplicado para aumentar a produção, mas a resposta da vida selvagem ao MP ainda é pouco conhecida. A altura da superfície do pasto (ASP) está relacionada ao MP e representa a estrutura da vegetação disponível ao gado e à vida selvagem. Aqui, analisamos a seleção de habitat da raposa-do-campo (*Lycalopex vetulus*) para sugerir um MP que beneficia tanto a produção quanto a conservação da espécie, usando a ASP como proxy do MP. Primeiro, medimos as taxas de expansão das pastagens em um agroecossistema no Cerrado brasileiro. Então avaliamos a seleção de habitat dessa espécie endêmica e vulnerável de raposa para pastagens sob diferentes MPs. Nós rastreamos trinta raposas por rádio-colar ao longo de dez anos e aplicamos Funções de Seleção de Recursos para estimar sua seleção de habitat sob duas ordens biológicas (área de vida e dentro da área de vida) em duas escalas de habitat (habitats classificados em escala grossa e em escala fina). Para habitats de classificação grossa, as raposas selecionaram pastagem sobre floresta em ambas as ordens biológicas de seleção. Para os habitats de classificação fina dentro de suas áreas de vida, machos e fêmeas selecionaram ASP média durante o dia e as fêmeas selecionaram ASP baixa durante a noite. Além disso, as raposas selecionaram pequenas plantações de milho em todas as escalas de classificação de habitat e ordens biológicas de seleção. Provavelmente, as raposas selecionaram ASP baixa e média para forragear, descansar, procriar e cuidar dos filhotes e selecionaram as plantações para se alimentar dos insetos presentes. Nossos resultados sugerem um manejo pró-raposa que pode ser aplicado a pastagens já convertidas e assim, reconciliar fazendeiros e raposas. O manejo pró-raposa é alcançado por meio de uma pressão moderada de pastejo sob sistema rotacional (proporcionando ASP baixa e média) e com a integração de pastagem com pequenas plantações de milho. Principalmente, o manejo pró-raposa pode beneficiar a produção de gado alinhada à conservação da raposa-do-campo.

Palavras-chave: conservação da biodiversidade; ecologia do movimento; Cerrado; mudanças de habitat; agroecossistema; manejo de fazendas.

Introduction

About half of the world's natural habitats have been converted into pasturelands for livestock raising (Jantz et al., 2015). Demand for ruminant meat is expected to more than double in the next decade (Tilman and Clark, 2014; Williams et al., 2017), despite recommendations to reduce meat consumption given climate change (Schiermeier, 2019). Pasturelands have played a central role in the global economy, but at the same time, pastures have negatively impacted biodiversity (Foley et al., 2005; Newbold et al., 2015). The pastureland's impact on biodiversity can be modulated by applied livestock grazing management (LGM), which is the manipulation of livestock grazing to achieve the production goals considering the responses of livestock, pasture, land, and economy (Vallentine, 2001). The LGM can affect wildlife species in different ways (Filazzola et al., 2020). A wide range of behavioral responses to pasture expansion and the LGM applied have already been shown (Graham et al., 2019; Koivula et al., 2018). These wildlife responses depend on species' traits, as well as the goals of livestock production (Filazzola et al., 2020). How to decrease pasturelands' negative impact on biodiversity while keeping the services provided by the meat supply chain is a socio-environmental conundrum that an adequate LGM can help to solve (Foley et al., 2005; Williams et al., 2017).

There are different models of LGM shaped to achieve the optimal economic outcome for each context of livestock production (Figueiredo et al., 2017; Groot et al., 2012). A key aspect of cattle production is that LGM must maximize animal performance, which is related to dry matter intake (O'Donovan and Delaby, 2008). The dry matter intake is regulated by grazing intensity, which regards how much time the animals spend grazing in a certain paddock (i. e. grazing pressure), and how many animals are grazing in a certain paddock during a certain time (i. e. stocking rate) (Laca, 2009; O’Connor et al., 2010; Sato et al., 2019). Grazing pressure and stocking rate modulate the pasture response to grazing that is observed by the resulted sward surface height (SSH) (la Motte et al., 2018). SSH has served farmers and grazers as a parallel measure of grass abundance, forage quality, and nutritional intake of their pasture to livestock (Realini et al., 1999). Given this, SSH assessments help to identify the consequences of LGM applied and to guide the necessary adjustments to achieve livestock production goals (Sone et al., 2020).

The SSH is related to the leaf:stem ratio of pasture vegetation and represents the available nutritional intake (Realini et al., 1999). The nutritional intake is greater during the initial growth of grass (more leaf than stem) but decreases as the grass gets old and stem increases (Amaral et al., 2013; Realini et al., 1999). Shorter SSH (<10 cm) mainly results from overgrazing (high stocking rates or long-grazing periods) and affects cattle production by decreasing the intake and nutritional content (Amaral et al., 2013; Realini et al., 1999). Furthermore, shorter SSH can cause soil exposure and erosion that jeopardizes the sustainability of production in the long term (Souza Filho et al., 2019; Sun et al., 2017). On the other hand, taller SSH (>50cm), due to long-rest periods, increases biomass availability by dead material accumulation on the sward upper stratum, but it is a low digestible forage that is poor in organic matter and protein, hindering animal's weight gain (Carnevalli et al., 2006; O’Donovan and Delaby, 2008). Therefore, it has been widely recommended that LGM's practice reaches medium SSH (e. g. through medium grazing pressure), which improves cattle performance and economic return just as it decreases environmental impact (Souza Filho et al., 2019; Sun et al., 2017; Tallowin et al., 2005).

Despite this recommendation, the lack of good LGM practices is widespread where the most global cattle production is concentrated: the developing countries

(Robinson et al., 2014; Schieltz and Rubenstein, 2016). Suboptimal LGM practices occur due to limited access to technical knowledge, assistance by landowners and farmworkers, and unstable socio-political scenarios (Melo-Becerra and Orozco-Gallo, 2017). It has contributed to the high rate of soil degradation, pastureland abandonment, and rural poverty across the world (Eriksen and Watson, 2009; Odadi et al., 2017). Furthermore, these suboptimal LGM practices worsen the future scenario for wildlife conservation, since they make restoration and its integration with conservation goals impracticable in many areas (Neilly et al., 2016).

Differential responses of wildlife to pasture expansion have been documented, from a strong selection of pasture (Andersen et al., 2017; Peters et al., 2015) to a sharp avoidance of it (Garcés-Restrepo et al., 2018; Kennerley et al., 2019). For those species that select for pasture, possible benefits include a supplementary area for foraging (Andersen et al., 2017; Crane et al., 2016), breeding (Ajder and Baltag, 2017), and shelter (Smith et al., 2019). However, species do not always select the habitat of suitable quality (Battin, 2004; Kristan, 2003), and pasture could be an ecological trap for some species, especially when mortality comes mainly from indirect anthropogenic causes (van der Meer et al., 2014). For some species specialized in open areas, whether the pasture is a favorable habitat remains uncertain, and there is still a gap in the understanding of how LGM can impact them (Smith et al., 2019). Even to open-area specialist mammals, the LGM impact on sward structure may affect forage quality and food availability (Monroe et al., 2017), affecting their behavior such as defense, rest, and foraging (Neilly et al., 2016). Moreover, how LGM practices that optimize economic return can affect the space use of open-area species of conservation concern remains little known.

Here we investigated the space use of a vulnerable, open-area specialized canid, the hoary fox (*Lycalopex vetulus*) (Lemos et al., 2013), inhabiting private cattle farms of the Cerrado, the Brazilian savanna. The Cerrado is a biodiversity hotspot (Myers et al., 2000) and around 70% of its area has been converted into pasture and crop fields (Sano et al., 2010), being the country's major agricultural frontier (Lambin et al., 2013; land cover change rate = ~0.5% yr-1). As far as it is known, the geographical distribution of the hoary fox is restricted to the Cerrado and its transition zones (Abra et al., 2020; Dalponte et al., 2018; Fernandes and Costa, 2013; Lemos et al., 2020; Olifiers and Delciellos, 2013). Therefore, hoary fox populations are declining and facing rapid habitat conversions (Lemos et al., 2020). The anthropogenic habitat dominating the geographical range of the hoary fox is pastureland. This pastureland is distributed on private cattle farms that are managed with a mix of LGM, resulting in a mosaic of SSHs (Pompeu et al., 2018). Even though ecological knowledge of the species is scarce, this canid seems to present some degree of tolerance to pasture areas (Dalponte 2009; Dalponte and Courtenay 2004; Rocha et al., 2008). The hoary fox mainly forages on soil termites and use armadillos' burrows to rest and nurse, and these important resources (food and shelters) are commonly found on pasture (Ferreira-Silva and Lima, 2006; Dalponte and Courtenay, 2004). Hoary foxes are monogamous and the couple's home ranges overlap (Lemos, 2016), but female and male mostly forage alone (Dalponte and Courtenay, 2004; Lemos and Facure, 2011). The species is nocturnal (Courtenay et al., 2006; Juarez and Marinho-Filho, 2002), so its active period occurs in a different time than cattle and farm main activities. Apparent pasture benefits have been confronted with its indirect negative impacts that are exacerbated at private farms, such as roadkill, poisoning and shooting (as retaliation to presumed domestic fowl predation), as well as persecution, killing, and parasite spillover by the contact with domestic dogs (Bickley et al., 2019; Brandão et al., 2020; Dalponte and Courtenay, 2004; Lemos et al., 2011; Ramos et al., 2020; Rocha et al., 2013; Rodrigues et al., 2015).

In the present study, we aim to evaluate the space use of hoary foxes related to pasture expansion and the applied LGM. To do this, we will first quantify pasture expansion rates on the study area, to guarantee that it represents the pasture expansion on the species' range - as it is our expectation. Then, we will investigate hoary fox habitat selection concerning pastureland, also addressing sex differences, given males and females exhibit some sex-specific behaviors (Lemos and Facure, 2011). Due to the open-area specialization of this species, we expect hoary foxes to select pasture in detriment of forested natural habitats (Dalponte and Courtenay, 2004; Lemos, 2016). Finally, we will investigate the hoary foxes' habitat selection concerning the different SSHs present on pasture, which represent the applied LGM (Realini et al., 1999). In this more detailed analysis, we will evaluate interactions with sex and time of the day, considering the activity periods of the species. We expect hoary foxes to select medium SSH at day and low SSH at night due to the periods of rest and foraging, respectively (Courtenay et al., 2006; Juarez and Marinho-Filho, 2002). As a result, we will discuss how our findings contribute to setting local strategies up for LGM practices that can boost both hoary fox conservation and the economic return of livestock production.

Methods

Study area

This study was carried out in a semi-intensive cattle farm complex, in the Limoeiro region (18°22'S, 48°07'W), located in the municipality of Cumari, southeast Goiás State, Central Brazil. In 2017, the Limoeiro region was declared a municipal Environmental Protection Area (Limoeiro EPA) composed of privately owned land.

Despite being an EPA, management has not been established towards reducing negative impacts of cattle production. The study area is an agroecosystem of approximately 150 km2 (Lemos, 2016) on an ecotone of the Atlantic Forest and Cerrado domains. It is originally composed of the semideciduous forest through the Paranaíba river basin intrusions, comprising an ecotone with high biodiversity (Lopes et al., 2012). Nowadays, more than 70% of the region is dominated by exotic pasture (mainly *Urochloa* spp.) used for cattle grazing, complemented by small patches of annual crops (mainly maize plantations) (Lemos, 2016). The local maize crop fields are small (~70 m2), near houses, and used for food supplementation to livestock during the dry season and also to sustain farm workers' families. Pastureland and croplands form a fragmented mosaic with natural forested vegetation of patches of seasonal and gallery forests (~21%) and cerrado *sensu stricto* (woodland savanna; 4%), without open natural vegetation (Lemos, 2016). This region presents a tropical climate with a dry winter (Koppen's Aw) with a cold dry period from May to September (19 °C mean temperature, 1.600 mm mean precipitation), and a hot wet period from October to April (30 °C, 1.900 mm) (Alvares et al., 2013).

Local livestock grazing management

The local farms apply semi-intensive management on livestock production: a non-confined, grazing-based system with mineral supplementation available all year round and some feed supply in the dry season. The average stocking rate is around 2 livestock units/ha; almost all beef cattle are Nellore breed (*Bos indicus*) or derived from crossbreeding. The herd is mainly for beef production and its proportion varies over the years among cow/calf (initial stage to raise beef cattle through a herd of cows and their calves) and backgrounding (intermediate stage to increase calves and young cattle weight) operations. The farms' size average is 2.75 km^2 with paddocks of 0.5 km^2 on average. The paddock fences are about 1.5 m height with 5 horizontal wires that do not prevent the hoary foxes' displacement. The paddock's pasture is predominantly planted with *Urochloa brizantha c.v. marandu*, with a few patches of *Urochloa humidicola, Panicum maximum* and *Hyparrhenia rufa*. Cattle are translocated among paddocks according to owners and/or farmworkers' subjective evaluation of sward vegetation structure and herd needs. Thus, the local LGM is flexible, without pre-established rest- and grazing periods. The SSH depends on grazing pressure, here defined by stocking rate and periods of grazing and rest (without grazing). Both extremes of SSH are present among sampled farms, as also more sustainable and rentable pastures.

Animal capture, handling, and tracking

Between 2009 and 2019, we carried several capture campaigns (4-50 days) to catch adult hoary foxes using Tomahawk® cage-traps baited with sardine. Captured individuals were anesthetized with a combination of 15 mg/kg ketamine (Cetamin 10 mg/ml, Syntec, Santana de Paranaíba, SP, Brazil), 0,5 mg/kg midazolam (Dormire 5mg/ml, Cristália Chemical and Pharmaceutical Products, São Paulo, SP, Brazil) and 0,2 mg/kg butorphanol (Torbugesic 10 mg/ml, Fort Dodge Laboratories, Fort Dodge, Iowa, USA) injected intramuscularly into the gluteal muscle. We weighed, sexed, and clinically examined the foxes to ensure their good health condition. Animals were then equipped with VHF- (ATS-Isanti® model 1950) or GPS-collars (Tigrinus®) and then released at the same place of capture. The VHF-collars were deployed between 2009 and 2017, while GPS-collars were used in 2018 and 2019. None of the tracking devices exceeded 3% of the animal's body mass (Lemos, 2016). Data from VHF radio-transmitters were collected mainly during the night by daily terrestrial-monitoring from 2009 to 2017. Most locations were obtained by direct homing-sighting, except when the habitat was inaccessible or there was interference, for that we used non-fixed bases triangulation (Boitani and Powell, 2012). GPS-satellite locations were obtained from two different temporal resolutions: fixed seven-hour intervals for all individuals and, for some foxes, also fixed thirty-minutes intervals. All procedures were approved by the Brazilian Government (Instituto Chico Mendes de Conservação da Biodiversidade ICMBio/SISBIO license number 14576-2) and by the Ethics Committee for the Use of Animals (Universidade Federal de Uberlândia, process number 089/14; CEUA/FMVZ-USP process number 8396120216), and followed the guidelines of the American Society of Mammalogists (Sikes, 2016).

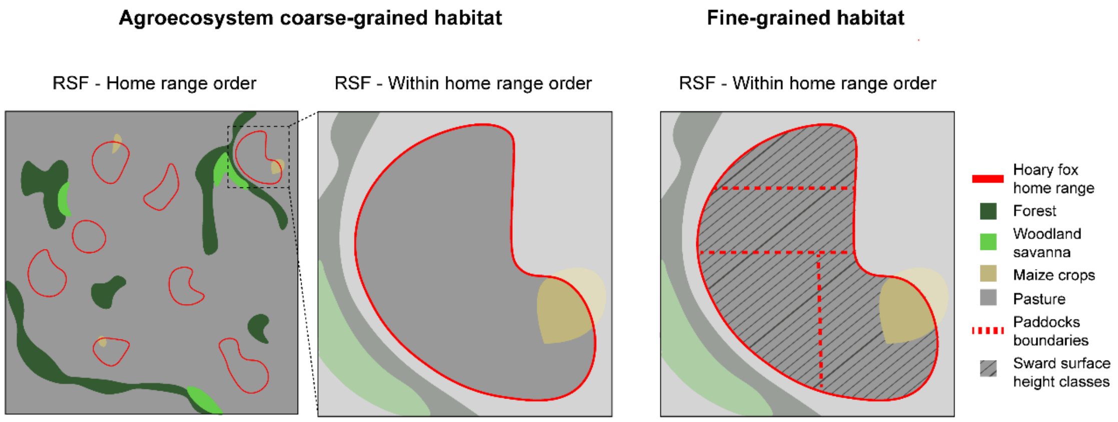
Coarse-grained habitat maps and temporal tendencies

Annual habitat maps for the study area were downloaded from Collection 4.1 of the MapBiomas database (Souza et al., 2020), with a resolution of 30 x 30 m. We identified three types of natural habitat classes (water bodies, forest, and woodland savanna), and two anthropogenic (pastureland and cropland - hereafter "maize crops" due to study area context). To assess the habitat changes through the last 35 years, we built a temporal yearly series of habitat maps from 1985 to 2019. We described the regional annual tendencies of habitat change by calculating the proportion of each habitat for each year. The annual maps concerning hoary fox monitoring time (2009 to 2019) were also the basis for the habitat selection analysis (see below Habitat selection section and Figure A.1). We carried out map manipulation in R software (R Core Team 2020) using the packages *rgdal* (Bivand et al, 2021), and *raster* (Hijmans, 2020).

Fine-grained habitat maps: pasture SSH as a proxy of LGM

To assess the spatial distribution of LGMs among farms, we classified the monthly pasture SSH for the paddocks within the area of GPS-monitored foxes during 2018 and 2019 (Figure 1). This temporal window of the GPS-satellite monitoring period enables matching detailed maps to detailed movement data. Here, the pastureland class,

Figure 1: The panel represents the two habitat scales (coarse- and fine-grained habitats) with the two biological orders of habitat selection analyzed (home-range and within home-range). Habitats and home range boundaries are illustrative.

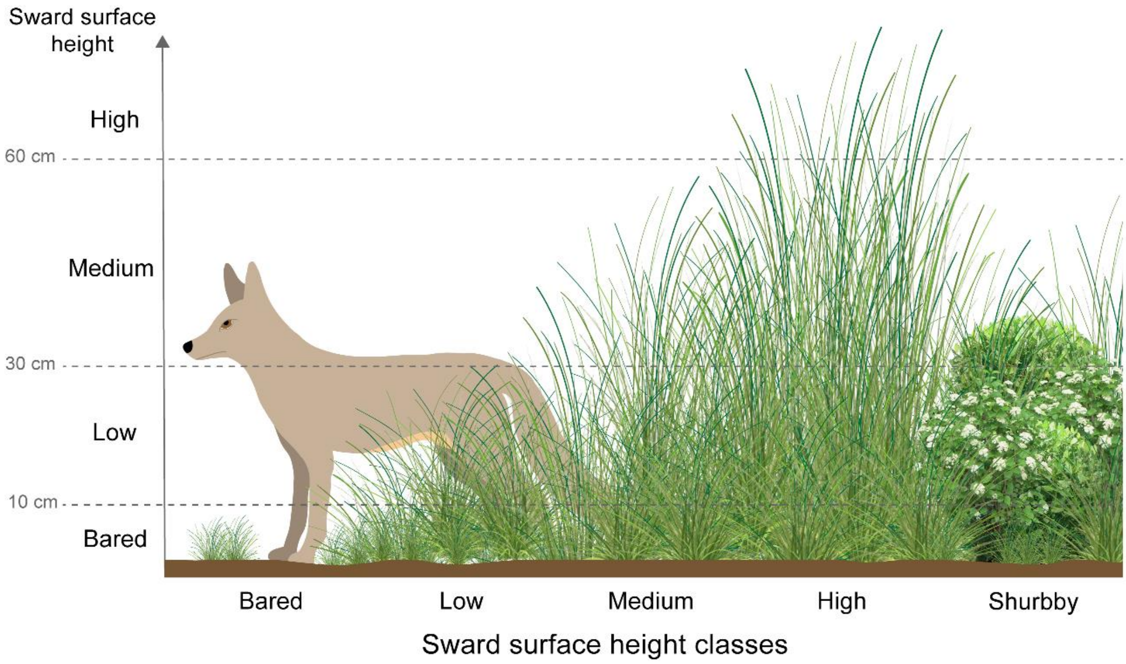


defined in the coarse-grained habitat maps, was subdivided into five new classes based on the observed SSH: (a) bared, consisting of areas with exposed soil and/or grass up to 10 cm tall; (b) low, SSH of 10-30 cm tall; (c) medium, SSH of 30-60 cm tall; (d) high, SSH taller than 60 cm; (e) shrubby pasture, tall exotic pasture with shrubs. The SSH classes were defined according to LGM categories (Amaral et al., 2013; Carnevalli et al., 2006) and hoary fox foraging behavior (Dalponte, 2009; Dalponte and Courtenay, 2004; Kotvikly et al. 2019; Lemos and Facure, 2011) and body size. This resulted in the SSH classes: (1) bared SSH, which can cover foxes paws; (2) low SSH, that can cover foxes legs; (3) medium SSH, that can cover foxes shoulders and head; and, (4) high SSH and (5) shrubby pasture, that would cover the whole fox's body (Figure 2). Paddocks were georeferenced on the ®Google Earth Pro software, and the pasturelands were monthly evaluated to assign the respective SSH classes. In the study area, the SSH of a certain paddock is assumed to be generally uniform due to (also uniform) grazing pressure applied to it. The SSH classification was made through scan-view in the field with a sward stick as reference (Stewart et al., 2001). The SSH monitoring was made monthly because SSH can change within paddocks throughout time. Therefore, we created monthly detailed maps of SSHs to match with detailed movement data.

Habitat selection

We analyzed the habitat selection of hoary foxes using Resource Selection Functions (RSF; Johnson, 1980; Manly et al., 2002). The RSF estimates the odds ratio of an individual to use a particular habitat class regarding its availability (Manly et al., 2002). RSF measures how animals select and avoid certain habitat classes with a null hypothesis that habitat classes are used according to availability (Manly et al., 2002). Here, RSF was run under two biological orders: second- and third-order of selection (*sensu* Johnson, 1980; Manly et al., 2002). The second-order (hereafter "home-range

Figure 2: Sward surface height classes considered to characterize pasture habitat according to livestock grazing management applied. An illustrative Hoary fox (*Lycalope vetulus*) to see the relation of its body size and sward surface heights.



order") figures out where the individual establishes its home range in the landscape, while the third-order (hereafter "within home-range order") depicts where the individual allocates its time within its home range. Furthermore, we evaluated the biological orders of selection using the two above-mentioned scales of habitat maps (coarse- and fine-grained). This enables us to evaluate how foxes use the space regarding coarse habitat classes, as well as fine SSH classes of pasturelands, which in turn capture different LGMs.

We applied the RSF in two perspectives concerning the detailing of movement and maps data: (1) we used the data of VHF- and GPS-collars and match these with the coarse-grained habitat maps to RSF analyses on home range and within home range orders; (2) only GPS-collars data were matched with fine-grained habitat maps to RSF analysis only within home range orders. In the first perspective, we investigated the interaction with sex, and in the second one, including more detailed data, we investigated the interaction with sex and period of the day.

The RSF is usually applied following the case-control scheme under a logistic approach (i.e. habitat used-habitat available). The habitat used is straightforward, being considered all observed locations of the individuals (coded as 1). On the other hand, habitat availability (code as 0) depends on the biological order of interest, and we created it using the *spsample* function at *sp* package (Pebesma and Bivand, 2005). For the home-range order, availability is measured based on a random sampling of locations from all individuals (1:1 ratio of used:random) in the entire study area, while for within home-range order, the random sampling of locations is constrained from each individual within the respective home range (Figure A.1). In this case, individuals' home ranges were estimated using fixed Kernel density probability under the isopleth of 95% and using the smoothing parameter of reference (Kernel 95%; Worton, 1989). The number of random locations sampled for each individual was twice the number of observed locations (1:2 ratio).

Used and available locations were matched with annual coarse-grained maps and monthly fine-grained habitats. The extracted values of locations and maps matched took into account the dates of acquisition; for instance, an observed individual location recorded in March 2019 was intersected with the fine-grained map from the same month and year. For each location, we also recorded the individual's sex and period of the day (day or night). We solved the RSFs using Generalized Linear Mixed Models with Poisson distribution available in the package *glmmTMB* (Brooks et al., 2017), following Muff et al.(2020) recommendations. We included habitat classes as an explanatory variable, as well as the interactions of habitat classes with sex, for coarse-grained habitats, and interactions of habitat classes with sex and with the period of the day (characterized as day from 06:00 to 17:59 h and as night from 18:00 to 05:59 h) for fine-grained habitats. The RSF analysis needs a habitat as a reference to compare the use of it to the use of other analyzed habitats and, then, to be able to model the selection of each habitat (Manly et al., 2002). Woodland savanna and bared SSH were set as the classes of reference for the coarse- and fine-grained habitats, respectively. We also included the individual identification as a random intercept to guarantee the use-availability ratio to be estimated within individuals (Duchesne et al., 2010).

Results

We captured 30 individuals (16 males and 14 females) for movement monitoring. Twenty of them were tracked through VHF-collars, and 10 (5 males and 5 females) were tracked using GPS-collars. The foxes monitored by GPS-collars were four couples with both males and females monitored, and more one male and one female unpaired. We obtained 1061 locations by VHF tracking devices ($\bar{x}$ = 53.05 locations per individual) and 6547 locations by GPS tracking devices ($\bar{x}$ = 654.7 locations per individual) (Table 1).

The study area presented a sharp tendency of habitat changes mainly due to the conversion of natural habitats into pasturelands (Figure 3). Between 1985 and 2019, the proportion of natural habitats (forests and woodland savanna) dropped from over 40% to only 23% (Figure 3B). Meanwhile, pasturelands that once covered about 57%, currently reached 80% of the study area. There was variability in the annual rate of change of natural habitats through time, with higher conversion rates into pasture from 1985 to 2009 (0,006%*$year^{-1}$), but with recent deceleration in the course of this study (2009-2019; 0.003%*$year^{-1}$) (Figure 3B). The monitoring of SSH in the paddocks revealed high spatial heterogeneity and high temporal stability in LGM applied in the pasturelands. During 2018 and 2019, the more representative SSH classes on paddocks were low (28%) followed by shrubby pasture (23%), bared and medium (22% each), and high SSH (2%). The pasture replacement to maize crops during the study period corresponded to 3% of the area.

Habitat selection

When evaluating the coarse-grained habitat selection, hoary foxes presented the same pattern of selection at both home-range and within home-range orders, with a few differences between the sexes (Table 2, Figure 4). Overall, males and females selected pastures ($\beta_{pasture}$ = 3.37, $p < 0.001$) and small maize crops ($\beta_{m.crops}$ = 3.25, $p < 0.001$) instead of natural forested habitats (β_{forest} = -1.99, $p < 0.01$). Individuals of different sexes selected pastures with the same strength ($\beta_{pasture:sex}$ = -0.12, p = 0.67), but males exhibited stronger selection for maize crops when compared to females ($\beta_{m.crops:sex}$ = 1.38, $p < 0.001$). Furthermore, females avoided the forest, while males used it according to its availability on both habitat selection orders ($\beta_{forest:sex}$ = 1.52, $p < 0.05$).

Table 1: General results of hoary fox (*Lycalopex vetulus*) monitoring at the study area (Limoeiro region, Goiás, Brazil) during the 2009-2019 period. The starting and final dates of all movement monitoring are highlighted in respective columns.

ID	Sex	Tracking device	Number of locations	Starting date (d/m/y)	Final date (d/m/y)	Years monitored	Days monitored	Locations per day
ID1	female	gps-collars	235	26/05/2018	06/08/2018	0,19	70	3,36
ID2	female	gps-collars	1288	29/03/2018	**22/05/2019**	1,15	413	3,12
ID3	female	gps-collars	676	29/03/2018	27/11/2018	0,66	238	2,84
ID4	female	gps-collars	230	25/03/2019	22/05/2019	0,16	57	4,04
ID5	female	gps-collars	1080	03/04/2018	21/03/2019	0,97	348	3,10
ID6	male	gps-collars	818	02/04/2018	28/11/2018	0,66	236	3,47
ID7	male	gps-collars	394	23/05/2018	25/09/2018	0,34	122	3,23
ID8	male	gps-collars	782	06/04/2018	27/11/2018	0,64	231	3,39
ID9	male	gps-collars	543	23/05/2018	27/11/2018	0,51	184	2,95
ID10	male	gps-collars	501	04/04/2018	04/05/2019	1,08	390	1,28
ID11	female	vhf-collars	26	01/11/2009	05/08/2010	0,76	274	0,09
ID12	female	vhf-collars	36	04/11/2009	01/10/2010	0,91	327	0,11
ID13	female	vhf-collars	91	14/04/2011	04/01/2015	3,72	1340	0,07
ID14	female	vhf-collars	93	15/02/2011	03/06/2015	4,30	1548	0,06
ID15	female	vhf-collars	42	12/03/2014	08/12/2014	0,74	266	0,16

ID16	female	vhf-collars	109	11/04/2011	06/06/2015	4,15	1495	0,07
ID17	female	vhf-collars	23	**23/10/2009**	08/07/2010	0,71	255	0,09
ID18	female	vhf-collars	21	01/05/2014	12/02/2015	0,78	281	0,07
ID19	female	vhf-collars	83	14/05/2013	04/06/2015	2,06	740	0,11
ID20	male	vhf-collars	22	29/03/2014	02/01/2015	0,76	273	0,08
ID21	male	vhf-collars	29	27/02/2014	03/12/2014	0,77	276	0,11
ID22	male	vhf-collars	40	28/03/2014	07/02/2015	0,86	309	0,13
ID23	male	vhf-collars	52	31/10/2009	07/05/2014	4,52	1627	0,03
ID24	male	vhf-collars	97	01/12/2011	18/10/2014	2,88	1037	0,09
ID25	male	vhf-collars	35	17/08/2014	29/05/2015	0,78	282	0,12
ID26	male	vhf-collars	64	07/11/2009	03/03/2012	2,32	836	0,08
ID27	male	vhf-collars	46	19/01/2012	30/06/2014	2,45	881	0,05
ID28	male	vhf-collars	64	06/02/2014	03/06/2015	1,33	477	0,13
ID29	male	vhf-collars	22	28/04/2014	01/12/2014	0,59	213	0,10
ID30	male	vhf-collars	66	13/05/2013	18/04/2015	1,93	695	0,09
			253,6 loc/ID			1,46 years/ID	524,03 days/ID	1,09 loc*day/ID

Figure 3: Changes in the proportion of coarse-grained habitats at the study area (Limoeiro region, Goiás, Brazil) during the 1985-2019 period (A). In (B), woodland savanna and forest class were grouped into a single habitat class named “woodlands”. Dashed lines depict the linear trend of habitat changes.

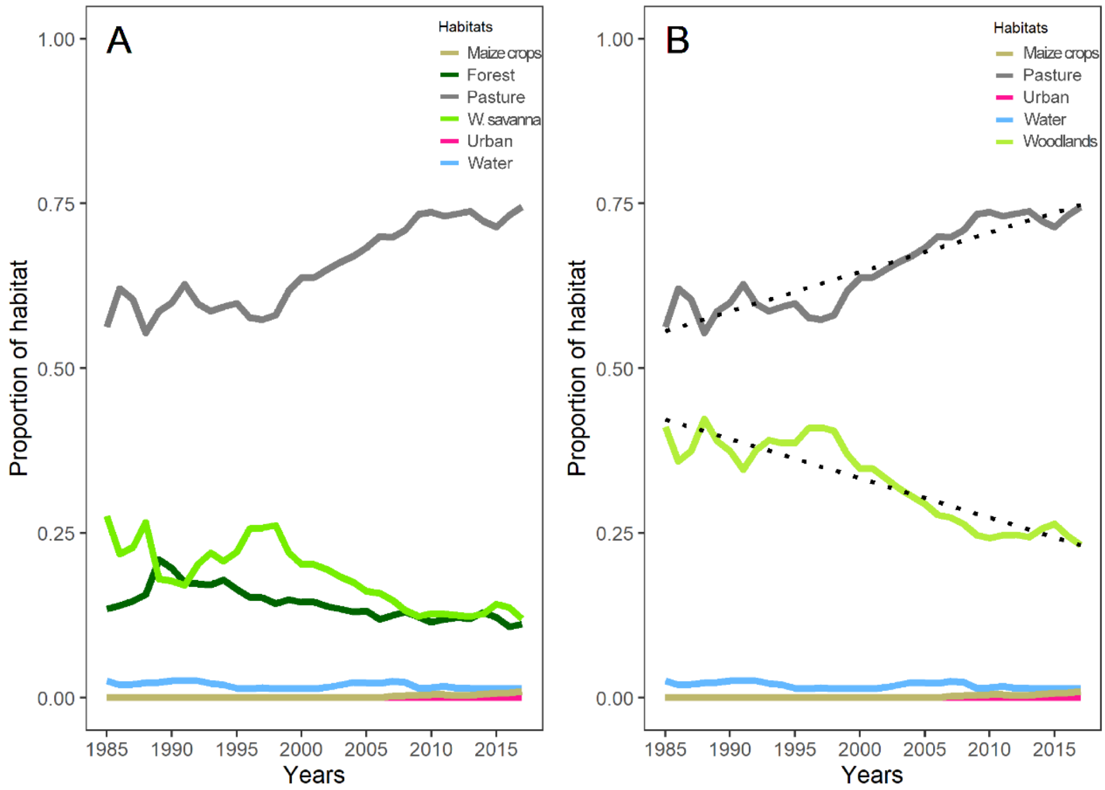
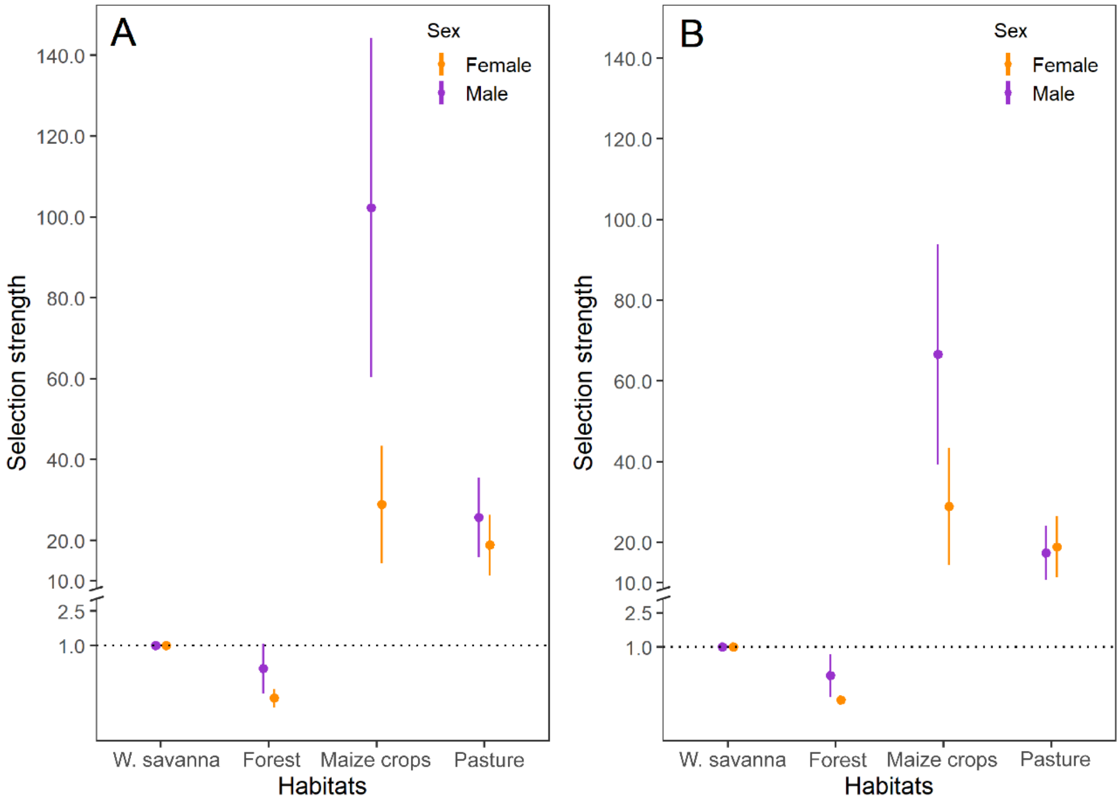


Table 2: Hoary fox habitat selection results (RSF) for coarse-grained habitat classes (maize crops, forest and pasture) on home-range and within home-range orders of selection considering the effect of sexes. Coefficients of selection that positives mean selection and negatives mean avoidance, standard errors, and p-values. Data from 30 individuals of *Lycalopex vetulus* monitored in 2009-2019 in the Limoeiro region, Goiás, Brazil.

	Home range			Within home range		
	Coefficient	Std. Error	p-value	Coefficient	Std. Error	p-value
M.crops	3.2498	0.2572	<0.001	3.3638	0.2582	<0.001
Forest	-1.9974	0.6117	<0.01	-2.0330	0.6124	<0.001
Pasture	3.3678	0.2048	<0.001	2.9363	0.2049	<0.001
M.crops:sex	1.3782	0.3322	<0.001	0.8345	0.3333	<0.05
Forest:sex	1.5166	0.6997	<0.05	1.3988	0.7004	<0.05
Pasture:sex	-0.1208	0.2841	0.6708	-0.0790	0.2843	0.7810

Figure 4: Hoary fox (*Lycalopex vetulus*) selection for coarse-grained habitats for males and females in (A) home-range and (B) within home-range order of selection. Selection strength values with confidence intervals (95%) touching the horizontal dashed line depict habitat classes used according to their availability, below represents avoidance, and above represents a selection of this habitat. Data from 30 individuals monitored in 2009-2019 in the Limoeiro region, Goiás, Brazil.



Having bared pasture as a reference habitat, when we evaluated fine-grained habitat selection at the within home-range order, males and females avoided the woodland habitats (forest and savanna) (β_{forest} = -16.38, p = 0.97 and $\beta_{w.savanna}$ = -0.52, p < 0.05) irrespective of the time of the day ($\beta_{forest:day\text{-}night}$ = 13.09, p = 0.98 and $\beta_{w.savanna:day\text{-}night}$ = -2.46, p < 0.001) (Table 3, Figure 5). The most strongly selected habitat were small maize crops, with the higher strength during the night when both sex selected (females more than males; $\beta_{crop:sex}$ = 2.49, p < 0.05), while during the day, males selected, but females avoided it ($\beta_{crop:sex:day\text{-}night}$ = -3.77, p < 0.001). Concerning the SSH classes, high SSH was avoided and shrubby pasture was generally avoided too ($\beta_{highSSH}$ = -1.84, p < 0.001 and $\beta_{shrubby}$ = 0.17, p = 0.39), but with some differences between sexes ($\beta_{shrubby:sex}$ = -0.53, p < 0.05). The most selected SSH class were medium ($\beta_{mediumSSH}$ = 0.38, p < 0.001), with slight changes between sex and time of the day. Males and females selected equally medium SSH during the day but avoided it during the night ($\beta_{mediumSSH:sex}$ = 0.11, p = 0.22 and $\beta_{mediumSSH:day\text{-}nigth}$ = -0.59, p < 0.001). Another SSH class selected was the low SSH, but with differences between the sexes across periods of the day. Females selected low SSH at night and used it according to its availability during the day, while males avoided it during the day and used it according to its availability during the night ($\beta_{lowSSH:sex}$ = -0.28, p < 0.01 and $\beta_{lowSSH:day\text{-}nigth}$ = 0.08, p = 0.14). Summarily, high SSH and shrubby pasture were avoided or used according to its availability, while low and medium SSHs were selected at least by one of the foxes' sex during a period of the day.

Discussion

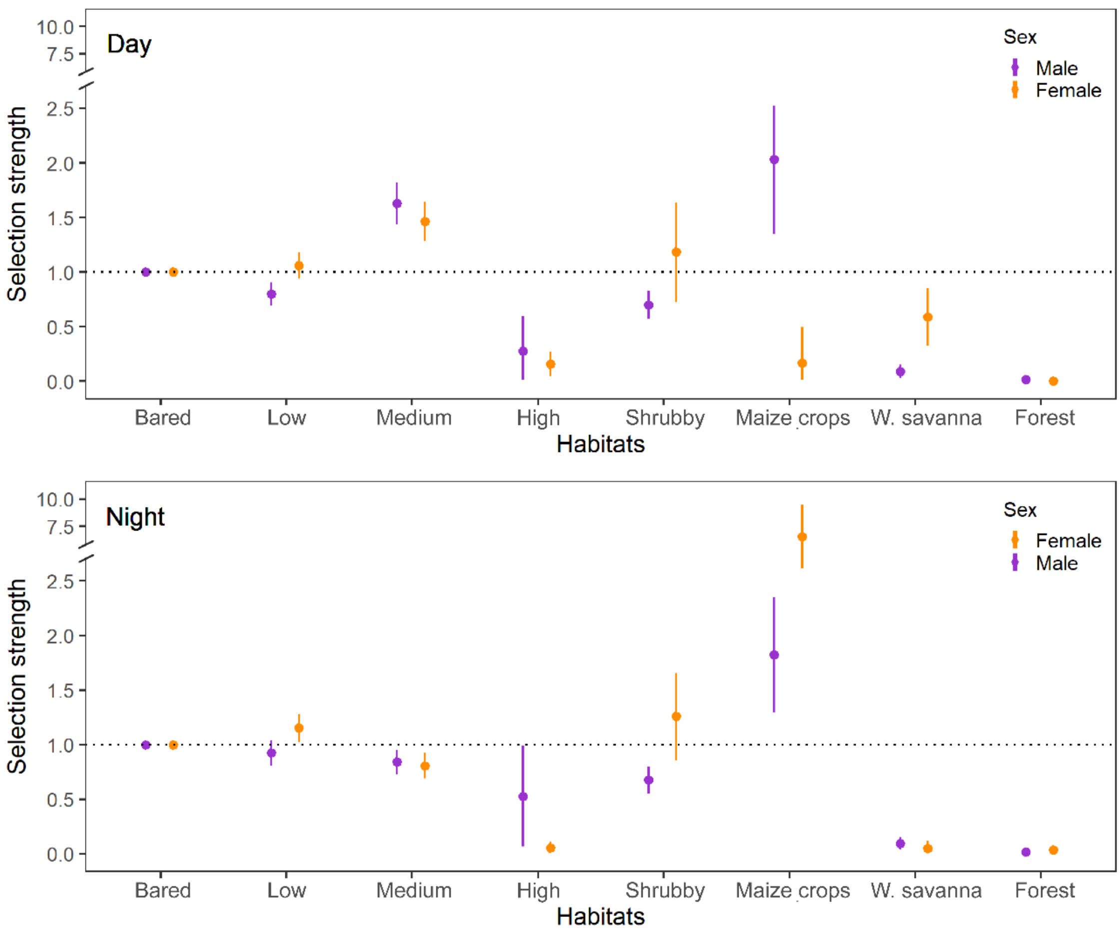
Information regarding the space use of wildlife helps to guide conservation actions, especially when the focal species lives in anthropogenic habitat under multiple negative impacts. This is the case of the hoary fox living in private cattle beef farms on Brazilian

Table 3: Hoary fox habitat selection results (RSF) for fine-grained habitats (shrubby pasture, maize crops, forest, woodland savanna and low, medium, high sward surface heights) considering interactions with sex and period of the day. Positives coefficients of selection mean selection and negatives mean avoidance, standard errors, and p-values. Data from 10 individuals of *Lycalopex vetulus* monitored in 2018-2019 in the Limoeiro region, Goiás, Brazil.

	Within home range		
	Coefficient	Std. Error	p-value
Shrubby	0.1674	0.1984	0.3990
M.crops	-1.7826	1.0034	0.0756
Forest	-16.3768	440.2541	0.9703
High	-1.8386	0.3604	<0.001
Low	0.0600	0.0580	0.3006
Medium	0.3818	0.0634	<0.001
W.savanna	-0.5307	0.2332	<0.05
Shrubby:sex	-0.5277	0.2198	<0.05
M.crops:sex	2.4925	1.0182	<0.05
Forest:sex	12.3195	440.2547	0.9777
High:sex	0.5527	0.6941	0.4259
Low:sex	-0.2853	0.0890	<0.01

Medium:sex	0.1073	0.0876	0.2207
W.savanna:sex	-1.8673	0.4255	<0.001
Shrubby:day-night	0.0621	0.2404	0.7961
M.crops:day-night	3.6639	1.0237	<0.001
Forest:day-night	13.0946	440.2545	0.9763
High:day-night	-1.0832	0.6772	0.1097
Low:day-night	0.0848	0.0574	0.1399
Medium:day-night	-0.5952	0.0757	<0.001
W.savanna:day-night	-2.4633	0.7438	<0.001
Shrubby:sex:day-night	-0.0909	0.2683	0.7348
M.crops:sex:day-night	-3.7727	1.0456	<0.001
Forest:sex:day-night	-13.0798	440.2556	0.9763
High:sex:day-night	1.7315	0.9811	0.0776
Low:sex:day-night	0.0612	0.0945	0.5176
Medium:sex:day-night	-0.0665	0.1053	0.5281
W.savanna:sex:day-night	2.5228	0.8772	<0.01

Figure 5: Hoary fox selection for fine-grained habitats for males and females considering time of the day. Values with their IC95% below represent avoidance, above represents selection, and touching the horizontal dashed line depicts habitat classes used according to their availability. Data from 10 individuals monitored in 2018-2019 in the Limoeiro region, Goiás, Brazil.



Cerrado, an open-area species that uses pasturelands and the few remaining natural open areas to live. We evaluated the space use of hoary foxes considering the conversion of their natural habitats to pasture and the LGM that are being applied. In an agroecosystem where there is no more open natural habitat, foxes selected pasture, but, when we evaluated pasture in detail, we found that they only selected low and medium SSH. These results show to us that some SSHs are more important to the species than others, information which we combined with livestock production knowledge to suggest pro-hoary fox management to ally cattle production and hoary fox conservation.

In our study area, the woodlands of Atlantic Forest and Cerrado were the only natural habitats that remained, with anthropogenic habitats being the only open areas available for hoary foxes. The species' avoidance of woodlands can be due to high predation by pumas (*Puma concolor*), with a record of more than 20% of one population killed by this predator (Lemos, 2016). Likewise, it can be due to the hoary foxes' specialization on open areas (Juarez and Marinho-Filho, 2002), which results in a consistent selection of pasturelands in the two biological orders evaluated within coarse-grained habitats. The hoary foxes' diet specialization on soil termites and the use of armadillo burrows as shelters (Dalponte, 2009; Juarez and Marinho-Filho, 2002) can also influence this selection pattern, since both resources are available in pastures (Attias et al., 2018; Negret and Redford, 1982). Those results agree with the expected tolerance of hoary fox for natural habitat conversion to pasture (Dalponte, 2009; Dalponte and Courtenay, 2004). However, the high conversion rates of natural to anthropized habitats jeopardized the biodiversity and the sustainability of the local ecosystem as a whole (Foley et al., 2005). The observed rate of land conversion into pasture at our study area, which matched the general trend recorded for the Brazilian savanna (Lapola et al., 2014), could not be so worrisome for hoary foxes in the next few years but can put at risk the sustainability of their habitat in the long-term (Gutiérrez et al., 2019).

In the fine-grained habitat scale studied, hoary foxes select pastures with different strengths among SSHs' categories. Both sexes selected medium SSH during the day and females selected low SSH at night. We believe that each SSH facilitates hoary foxes' movement and provides food and shelter in different magnitudes, as observed for other species (Neilly and Schwarzkopf, 2017; Pettigrew and Bull, 2011). Medium SSH provides refuge for hoary foxes since it favors natural shelters (Lemos, 2016), covering their bodies and the surroundings of armadillo burrows used by them. Besides, the fact that individuals only select medium SSH during their resting period (daytime) indicates that this is likely related to the availability of shelters and not necessarily related to the permeability of movement. On the other hand, the sexual difference of low SSH selection during the hoary fox active period (night) suggests that females found some benefits on foraging in this habitat, a benefit that seems not to be sufficiently advantageous to males. Females of other canids species seek more protection during their activities than males (Holekamp et al., 2000). The same can happen to hoary foxes, where females can find protection by low SSH during foraging, while males rather forage in riskier habitats (as bared SSH and maize crops). This could be confirmed with future studies on hoary fox behavior, which would help clarify the sexual differences on low SSH selection.

Maize crops were selected in both habitat scales (coarse- and fine-grained) on the two biological orders (home range and within home range) analyzed, which was unexpected given the scarcity of previous records of hoary foxes on any crop type. Hoary foxes selected crops with a strength five times bigger than the most selected SSH, but the use of this habitat is not uniform over time. During the field monitoring, we observed hoary foxes on maize crops only during the initial growth of maize, when the height of the crop was low, and after harvest, when maize straw accumulates on the soil and attracts small mammals (Heroldová et al., 2007). These behavioral records matched with the species' stronger selection for maize crops at night, reinforcing the suggestion that foxes may forage in this habitat (Ferreira-Silva and Lima, 2006; Kotviski et al., 2019). In a context without natural open areas available to hoary foxes, the acknowledgment that small maize crops can provide supplementary food sources, opens up a new avenue to apply farm management that provides said crops combined with the essential SSH on pastures. Yet, it is worth noting the tiny size of maize crops and the familiar destination of maize production in our study area. The local reasons for this type of maize production (subsistence and supplementation for livestock) are similar to medium-scale farms in other developing countries (Herrero et al., 2010). We can take good examples of said management models (Melo-Becerra and Orozco-Gallo, 2017; Nampanya et al., 2012; Sempore et al., 2016) to find a strategy that can enhance the sustainability orientation that Brazilian farms need (Lapola et al., 2014) – hence benefiting both wildlife and the economy of cattle production (Foley et al., 2005; Graham et al., 2019).

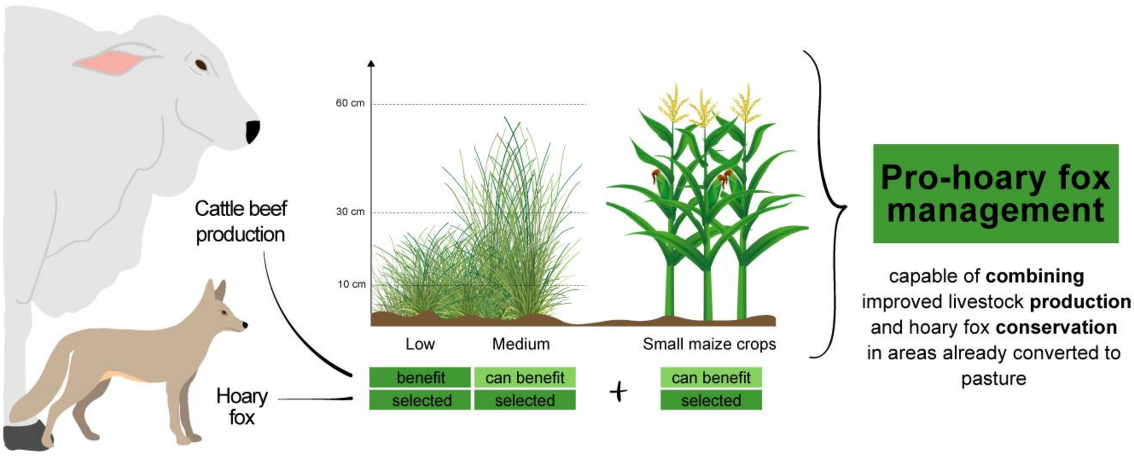
Integrated farm management is the combination of more than one production on-farm (Sanderson et al., 2013). In the hoary foxes' case, the integration of small maize crops with the essential SSH on pasture can provide a complementary food source and suitable open areas, respectively. The hoary foxes' selection of these three habitats takes us beyond our expectations of suggesting LGMs practices and modify pasture heights. In fact, our suggestion concerns farm management as a whole, where integrated farm management seems to be a way to provide the habitats selected by hoary foxes and keep the goods for farmers. Fortunately, the most selected SSHs by hoary foxes can also produce the best economic outcome for farmers (Souza Filho et al., 2019; Tallowin et al., 2005), and small subsistence crops (as maize crops) can provide social and economic benefits (Sanderson et al., 2013). Therefore, agroecosystems on the Brazilian savanna with no more open natural habitats can be rentable for farmers and suitable for the species by applying what we named as pro-hoary fox management – the integration of medium and low SSH on pasture with small maize crops. We highlight that our management recommendation concerns only the habitats already converted into pasturelands, which does not lessen the need for natural habitats protection - especially the neglected open habitats (Bonanomi et al., 2019). Our results help enhance the cattle beef farms to better suit hoary foxes' survival, but we still ignore if pasture expansion creates ecological traps to the species and if the species is benefited from this conversion (Gutiérrez et al., 2019). To find this out, populations living in natural and anthropogenic open areas need to be compared, and agroecosystems with different contexts. Yet, it's possible to improve the suitability for hoary foxes in already deforested areas by promoting better human-hoary fox interactions, mitigating other negative impacts brought by livestock production (Dalponte and Courtenay, 2004; Lemos et al., 2011), and shifting the current LGMs to the pro-hoary fox management proposed here (Ahlering and Merkord, 2016; Bickley et al., 2019; Pinto-Correia et al., 2018).

Farmers can apply a pro-hoary fox management in Brazilian savanna by managing their cattle herds with time-controlled rotational grazing across paddocks under moderate grazing pressure (Odadi et al., 2017), and integrating small maize crops on farms. The time to manage the herd from one paddock to another and how much is "moderate" grazing pressure to reach medium and low SSH will depend on cattle breeds, local rainfall, grass species, soil nutrition, and many other local factors (Briske et al., 2008; Tesk et al., 2018). Thus, we recommend periodic evaluations of pasture SSH to ensure the effectiveness of the managing practice, considering economic and ecological long-term goals (Briske et al., 2008; Teague and Barnes, 2017). The managing practices are benefiting when designed specifically to the local context (Latawiec et al., 2014) and supported by social-political initiatives (Garnett et al., 2013). Our study reinforces the necessity of policies with shared social, agriculture, and environmental goals by the Brazilian government (Loyola, 2014; Vieira et al., 2018). Furthermore, wildlife-human contact increases as more land conversion happens, turning strategies that promote coexistence between human development and environmental conservation more necessary (Foley et al., 2005). Scientific research that obtain information on wildlife space use in anthropogenic habitats can provide valuable information to help government policies to design these coexistence strategies (Lambin and Meyfroidt 2011; García et al. 2013; Latawiec et al. 2014), as it is our purpose for the pro-hoary fox management.

Conclusions

We found out the habitats selected by hoary foxes living in an agroecosystem with open natural areas already converted into pasture. Pasturelands with medium and low sward heights and small maize crops were the habitats selected by the species. Considering these results, we were able to suggest a pro-hoary fox management strategy to be applied in cattle beef farms of the Brazilian savanna (Figure 6). Pro-hoary fox management can benefit conservation of this species as well as livestock production in economic and sustainable ways. Using the hoary fox as a model, our study shows how the combination of knowledge about wildlife space use and management of anthropogenic production activities can guide actions to mitigate human impacts and improve human-wildlife coexistence.

Figure 6: The suggestion of pro-hoary fox management for areas already converted to pasture, an application of hoary fox habitat selection results combined with cattle beef production knowledge.



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