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Landowner perceptions of livestock predation: implications for persecution of an Amazonian apex predator

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Abstract

Apex predators are widely threatened globally and generally considered a priority on the conservation biology agenda. The harpy eagle, *Harpia harpyja*, is an apex predator threatened by habitat loss and persecution and a flagship species for Neotropical conservation. We investigated the roles of social, economic and environmental factors related to livestock depredation by harpy eagles, causes of reported harpy eagle persecution by local landholders and the intent of future harpy eagle killings. We explored these issues using structured interviews with 184 local livestock owners, who had admitted killing a combined total of 181 harpy eagles. We found that livestock abundance and livestock husbandry were the best positive predictors of levels of self-reported livestock predation by harpy eagles. Domestic livestock reported to be killed by harpy eagles (192) were mainly chickens (47.9%), followed by goats (22.4%), pigs (18.2%) and sheep (8.3%), with pets representing only ~3% of kills. Few harpy eagle killings were related to livestock predation, which accounted for less than 20% of all eagles killed. Instead, the main reason for killing harpy eagles was simple curiosity, and many interviewees reported later regretting their acts. Regarding intent to kill harpy eagles in the future, interviewees' perceptions of the threat posed to livestock and humans by eagles, and the subjective norm, were unrelated to intent to kill harpy eagles further. The single most important factor in predicting intent to kill harpy eagles was whether the interviewee had suffered livestock predation by eagles in the past. Additionally, the intention to kill eagles was negatively associated with landholding size. Most of our interviewees were relatively large landowners, but they are typically outnumbered by smallholders who are more likely to persecute harpy eagles. Consequently, education, compensation and tourism activities should be directed to smallholders to mitigate unnecessary persecution and mortality of harpy eagles.

Introduction

Apex predators are important components of fully functioning ecosystems (Terborgh *et al*., 2001; Humphries, Hill & Downs, 2015; Cunningham, Johnson & Jones, 2020). By keeping herbivore populations in check, both by direct predation (Le Roux *et al*., 2019) and fear induction (Barnett *et al*., 2017, 2018), they play important roles in animal habitat and resource use (Menezes, Mourão & Kotler, 2017). These traits, combined with the requirements of typically large home ranges (McBride & Thompson, 2018), habitat quality and a suitable prey base (Lamichhane *et al*., 2018), mean they have high priority on conservation biology agendas, both as umbrella and flagship species (Terborgh & Estes, 2013). Conversely, apex predators often pose risks to human lives (Khan, 2009; Murphy, 2020), are relatively expensive to study (Morato *et al*., 2018) and are frequently disliked and feared by local communities (Bhattarai *et al*., 2019). Together, these elements can make apex predator conservation extremely challenging (Ibanez *et al*., 2016).

Predation on domestic livestock is often related to apex predator persecution by affected livestock owners (Terborgh & Estes, 2013; Mondragón *et al*., 2017). This issue has been a component of apex predator conservation since the dawn of predator research (Leopold, 1949). However, much of this tradition has its origins in the northern hemisphere (Bonnet, Shine & Lourdais, 2002), especially with mammalian Carnivora that are typically the main apex predators in such ecosystems (Makarieva, Gorshkov & Li, 2005). Research in tropical regions mirrors this focus, with extensive research on mammalian carnivores (Eklund *et al*., 2017; van Eeden *et al*., 2018). Tropical guilds of apex predators are, however, highly diverse (Glen & Dickman, 2014; Murphy, 2020). In tropical ecosystems, pythons (Goursi *et al*., 2012), anacondas (Miranda, Ribeiro Jr & Strüssmann, 2016), crocodilians (Corvera, Manalo & Aquino, 2017) and large eagles (McPherson, Brown & Downs, 2016; Restrepo-Cardona *et al*., 2020) all prey on livestock – and pose conservation challenges similar to those of mammalian carnivores.

The harpy eagle, *Harpia harpyja*, (Fig. 1) is perceived by local people as a livestock predator throughout its Neotropical distribution range (Sick, 1984; Trinca, Ferrari & Lees, 2008; Curti & Valdez, 2009; Godoi *et al*., 2012). Harpy eagles are apex predators that prey on >100 species of arboreal vertebrates (Miranda, 2018). These prey are usually arboreal mammals, especially sloths and primates, but also large birds such as cracids (Miranda, 2015). Terrestrial vertebrates in general, especially ungulates, are rarely consumed as prey (Miranda *et al*., 2018; Miranda, 2018). As with many apex predators, harpy eagles occur at relatively low densities (8–12 breeding adults/100 km²; González & Vargas, 2011). Harpy eagles have undergone a 40% reduction in their distributional range since the 19th century (Miranda *et al*., 2019). These threats are being incorporated into IUCN assessments, since the species was considered Near Threatened in the last evaluation (Birdlife International, 2017). Although local communities frequently report that harpy eagles take domestic livestock as prey, this has been rarely documented in the literature, although their diet is one of the better-studied aspects of their biology.

Predators can include domestic animals in their diet as a response to habitat degradation or alteration (Zuluaga & Echeverry-Galvis, 2016; Mondragón *et al*., 2017). The Amazonian Arc of Deforestation is a degraded area that covers the southern, south-eastern and eastern border of the Amazonian biome and has been intensively degraded (Roriz, Yanai & Fearnside, 2017). The Amazon region comprises 93% of the harpy eagle's current distribution range (Miranda *et al*., 2019; Sutton *et al*., 2020). The killing of harpy eagles is reported across this region (Gusmão *et al*., 2016), but the causes of the killings are poorly known (Trinca, Ferrari & Lees, 2008). Local inhabitants also mention perceptions such as curiosity and a possible threat to livestock as reasons for those killings (Trinca, Ferrari & Lees, 2008; Gusmão *et al*., 2016). Additionally, perception that large eagles are a threat to humans is frequent and widespread (Curti & Valdez, 2009; Watson *et al*., 2016). Any anthropogenic mortality is a potentially serious impact on a local harpy eagle population because of their low reproductive rate: a pair requires 30–36 months to produce a single eaglet, which in turn requires 6 years to reach sexual maturity (Muñiz López, 2016). The killing of harpy eagles has been approached exclusively by descriptive studies (Giraldo-Amaya *et al*., 2020), and the circumstances modulating underlying causes remain unknown.

Several frameworks have been proposed to promote conservation of large predators that prey on domestic livestock. The Theory of Planned Behaviour (TPB) proposes that a subjective social norm (regarding a behaviour) and a perceived behavioural control, combined with attitudes towards the behaviour, predict behaviour intention, which in turn causes the actual behaviour (Marchini & Macdonald, 2012). Perceived behavioural control refers to a person's perceptions of how easy or difficult performing a behaviour is, such as

Figure 1 Harpy eagle preying on a rooster (*Gallus gallus*; a), a lamb (*Ovis aries*; b) and a domestic kitten (*Felis catus*; c). Although local livestock owners recognize harpy eagles as predators of domestic livestock, there were no formal studies on this topic before the present study. (Photo credits: Francisca do Carmo Firmo (b), Robson Silva e Silva (a and c)).

breaking the law by shooting predators (Swan *et al*., 2020), or complying with land use regulations regarding property size (Zuchiwschi & Fantini, 2015; Zimbres, Machado & Peres, 2018). For instance, the traditional beliefs of pastoralists in Kenya underpin their attitudes regarding cattle management and lion *Panthera leo* predation (Perry *et al*., 2020). In this case, the subjective social norm is that those who properly manage cattle succumb to lower lion predation. Still, the perception of behavioural control leads to variation in management since some pastoralists cannot perform certain livestock management practices because of logistic and economic limitations (Perry *et al*., 2020).

Perceived behavioural control increases in larger rural private landholdings (e.g. perceived lack of law enforcement), and consequently, so does predator mortality in response to livestock predation (Marchini & Macdonald, 2012). Besides perceptions, other aspects must be considered: livestock abundance, landscape traits (such as forest proximity) and livestock management techniques can also influence livestock predation rates (Palmeira & Crawshaw, 2008; Restrepo-Cardona *et al*., 2019). Knowing the social, environmental and psychological drivers that motivate harpy eagle killings – as well as the livestock species most likely to be attacked – is critical for predicting, and consequently preventing or reducing such events. Therefore, filling this information gap should ensure fine-tuning of conservation actions by governmental, and non-governmental organizations and the private sector, through practices such as environmental education or financial compensation for livestock losses.

To enhance our understanding of the motivations for the killing of harpy eagles by local livestock owners and the extent of this behaviour, we explored the social, economic and environmental drivers of such activities. We tested assumptions expanding from the Theory of Planned Behaviour, as well as hypotheses related to the livestock predation framework, as described below: Hypothesis I: people's perception of the risk posed by harpy eagles to their livestock determines their predisposition to kill eagles. Hypothesis II: people's perception of the risk posed by harpy eagles to people safety determines their predisposition to kill eagles. Hypothesis III: previous experience of livestock predation by harpy eagles drives eagle persecution. Hypothesis IV: beyond the retaliatory or preventive killing (hypotheses I–III), subjective norm and perceived behavioural control affect the killing of harpy eagles. Hypothesis V: perceived behavioural control is affected by ranch size, and consequently, are harpy eagle killings. Hypothesis VI: Harpy eagle predation on livestock depends on particularities of the ranches, their location and the livestock management.

Materials and methods

Study area

This study was conducted in the southern portion of the Amazonian Arc of Deforestation, in the state of Mato Grosso, Brazil (Fig. 2). We conducted interviews in 10 municipal counties or a total area of 149 394 000 ha.

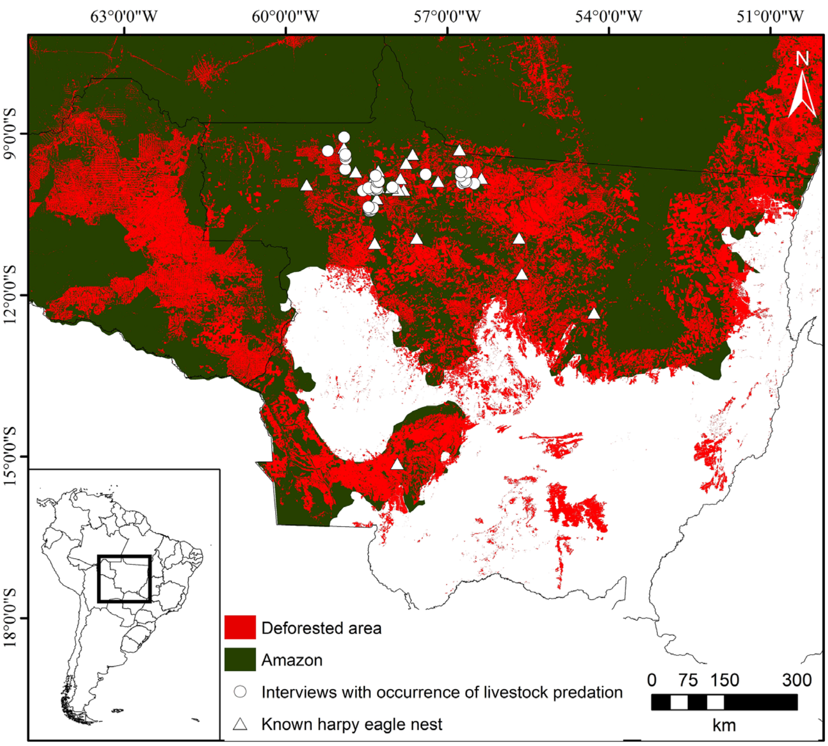

Figure 2 Study landscape, showing locations where interviewees reported the occurrence of livestock predation and the location of harpy eagle nests we monitored.

Koppen (1948) classifies the regional climate as “tropical monsoon climate”. Annual rainfall averages 2350 mm, and ambient temperature averages 24.5°C, combined with high relative air humidity (80%–85%; Radam-Brasil, 1983). Several indigenous groups exclusively inhabited this portion of the southern Amazon up to the 1970s (Villas Boas & Villas Boas, 1994). Nowadays, the region is dominated by cattle ranching, with smaller portions of land allocated to grain (soy and maize) production (Junior & Lima, 2018). Forest cover is present only as remnants within a hyper-fragmented landscape.

The Arc of Deforestation was created by state-sponsored migration programmes in the 1970s (Schneider & Peres, 2015). Population density is relatively low, with 1.6 ind./km² (IBGE, n.d.). The migration generated a land-occupation structure comprised of: (1) relatively small properties (smallholdings, ~20–100 ha) often resulting from state-sponsored agrarian settlement programs (Wittman, 2010); and (2) large holdings (500–150 000 ha), often resulting from immigrant farmers and ranchers who swapped small landholdings in southern and south-eastern Brazil for larger tracts of cheaper land in the Amazon. These private properties are located adjacent to protected areas and indigenous territories that account for 15 million hectares in the state of Mato Grosso (Begotti & Peres, 2020). Cattle ranch headquarters in large holdings are typically surrounded by pasture and located far from the forest (Michalski *et al*., 2006), but within smallholdings are frequently near remnant riparian forests (Oliveira *et al*., 2013).

Although cattle ranching is the main economic activity in the study region (Fearnside, 2005; Schneider & Peres, 2015), smaller livestock is frequently raised on properties of all sizes. Of the domestic livestock kept by landowners, chickens *Gallus domesticus* are the most common (707 947 head), but smallholders typically also keep pigs *Sus domesticus* (77 669 head), sheep *Ovis aries* (37 268 head) and goats *Capra hircus* (5477 head; IBGE, n.d.). Small livestock within the 10 counties where we conducted our interviews are used for food, commerce and barter (Gasques *et al*., 2012; Chávez, 2017). Small-bodied livestock are always kept near farm houses, so we assumed that landowners’ level of predation detection is the same, independently of property size. Pet dogs *Canis familiaris* and cats *Felis catus* are also common, particularly around human habitation, but statistics on ownership are unavailable. Further details on study counties are available in Supporting Information Table S1.

Migrant ranchers are mainly from southern Brazil (Schneider & Peres, 2015), and although racial mixing with indigenous communities occurred (Tavares *et al*., 2019), the culture retains strong European cultural roots (De Majo & Relly, 2020). They do not enjoy eating wildlife other than ungulates and ungulate-like large rodents (Trinca & Ferrari, 2007). Therefore, poaching of arboreal vertebrates is limited to gamebirds (Michalski & Peres, 2017), and is non-existent for other animals such as primates and sloths (Michalski & Peres, 2005; Trinca & Ferrari, 2007). Given the structural connectivity of the remaining fragments resulting from riparian corridor set-asides, as demanded by Brazilian forest legislation (Anonymous, 2012), assemblages of medium to large-bodied vertebrates in the remaining forest canopy remain relatively intact (Lees & Peres, 2008; Michalski, Metzger & Peres, 2010; Zimbres, Machado & Peres, 2018).

Structured interviews

The process of interviewee selection was based on the premise that the interviewee had killed or attempted to kill a harpy eagle, regardless of his/her motivations. We found our interviewees whilst putting up posters announcing a reward for anyone aware of a harpy eagle nest. These posters were placed in sport fishing stores, Brazil nut harvesting associations and farm supply shops (where most encounters happened). People normally approached us affirming they had shot ‘this hawk’ (as recent migrants, locals generally do not label harpy eagles as an eagle and have no specific name for it). Besides affirming that they had personally killed a harpy eagle, it was common for locals to declare that a friend, neighbour, relative or acquaintance had done so. On these occasions, we asked for the contact of such a person, thereby accumulating interviews.

To confirm raptor species identification, we asked for photographs of killed harpy eagle individuals and body parts. We tested the interviewee’s harpy eagle call recognition skills using a playback. To rule out false identifications, we also showed a sheet of colour photographs including an adult harpy eagle, together with other native and exotic eagle species of similar appearance but from other continents, and asked the informant to identify which eagle species they had killed. In cases of livestock predation, playback of harpy eagle calls triggered predator-avoidance behaviour in livestock, helping to validate further confirmation of predator identity (Dissegna, Turatto & Chiandetti, 2018; Makin, Chamaillé-Jammes & Shrader, 2019).

Harpy eagle persecution is illegal in Brazil and can be a sensitive topic for landowners and their employees (Trinca, Ferrari & Lees, 2008). Consequently, we took the following steps to avoid systematic biases during interviews: (1) all interviews were conducted by EBPM, who was always accompanied by a local, well-known resident who first explained to the landowner that we had no relationship with law enforcement nor environmental authorities; (2) we affirmed that the information shared would remain strictly confidential and anonymous; and (3) we informed interviewees that we were interested in designing solutions to their perceived harpy eagle human–wildlife conflicts. On several occasions, people offered to be interviewed – including offers of certain harpy eagle parts – after they were told that we were trustworthy by a neighbour who had been interviewed previously.

Interviews were usually conducted on the site where we met the landowner, except for cases with livestock predation. In those cases, we visited the property to collect additional data. The interviewees answered the questionnaire themselves while we remained available to answer any questions. If interviewees were illiterate, partially literate, or had vision issues, we read the questions to them, and they were presented with a set of graphic 'smiles' that also ranged between 'highly agree' and 'highly disagree'. Our questionnaire is available as supplementary information. We followed all standard ethics related to local interviews and strictly adhered to ethical guidelines from the State of Mato Grosso University (CEP-Unemat, 25/2016).

Likert scale

The Likert scale is a psychometric scale frequently used in research that uses questionnaires (Bruskotter & Wilson, 2014). Likert scaling is a bipolar scaling method, measuring the positive, neutral or negative response to a statement, and is therefore useful for wildlife conflict issues (Marchini *et al*., 2019). We measured six components of the Planned Behaviour Theory according to Moleón *et al*. (2011). Local perceptions were divided as follows: (1) Tourism, related to knowledge of harpy eagle as a species of touristic interest; (2) Perceived livestock predation, with a series of statements related to consumption of livestock by harpy eagles; (3) Subjective norm, on which we checked the subjacent issues and views about harpy eagles; (4) Perceived behavioural control, regarding personal views about law enforcement; (5) Conservation, for which we measured perceptions about common environmental issues; and (6) Outcomes, regarding the chances of further harpy eagle killings. A complete list of statements related to each subject is presented in Table 1. The perception of each statement was recorded on a scale of 1–5 (highly agree to highly disagree, with 3 as the neutral response). The Cronbach's alpha (Cronbach & Meehl, 1955) was used to check the consistency of the resulting data.

Livestock predation

To test hypothesis VI, we built a domestic livestock husbandry index (LHI) based on the level of domestic livestock management in place at each landholding where at least one case of livestock predation had been reported. This LHI was based on the degree to which shelter and food were provided. In each case, we noted values of 0, 0.5 and 1 for absent, partial and permanent food or shelter. Values were obtained for each domestic livestock species separately, and then all values were summed for a given landholding. We then divided this value by the number of domestic livestock present and divided the resulting value by two (to account for food and shelter). The resulting value varies from 0 to 1. Therefore, the higher the grade obtained in the LHI, the higher the level of husbandry management received by domestic animals within any property, with 1 representing all species having shelter and regular food. Pigs in large fenced areas that included riparian forest and wetlands sections – but no sheltered pig housing – were defined as free ranging. We added physical shelter to the odds of predation by harpy eagles because they lower predation risk if livestock could take shelter from any predation threat (Bickley *et al*., 2019; Mhlanga *et al*., 2019). Lack of regular food provision requires animals to expend more time foraging, and domestic animals typically exhibit low anti-predation vigilance rates while foraging (Brown & Kotler, 2007; Whelan & Schmidt, 2007). We calculated market prices per kg of live livestock body mass based on real transaction values in the study region, which were determined during each interview.

Table 1 The set of statements and questions measured in the present study that are explicitly related to the perceptions of each interviewee in relation to harpy eagles (HEs)

Theme	Statement
Tourism	Do tourists want to see HEs?
	Do you have an interest in tourism?
Livestock predation	Would you implement methods for preventing livestock predation?
	Do you think there should be monetary compensation for livestock losses?
	The HE is a threat to livestock
	The HE is a threat to humans
	In this private landholding, we cannot tolerate HE capturing livestock
Subjective norm	My neighbours approve of the killing of HEs that attack livestock
	My family approves of killing HEs that attack livestock
	My neighbours kill HEs that attack livestock
	My neighbours are my friends
Perceived behavioural control	If I kill a HE on my property, it is my problem
	The government must be held responsible for the HE problem
	HE attacking livestock is an acceptable problem
	Each property should solve this problem on its own
Conservation	I would be very happy if there were no HEs
	HEs need to be protected
	I would like help with resolving the HE issue
	The Amazon is adequately protected
	I consider myself aware of the conservation problems of the Amazon
Outcomes	I will kill the next HE that attacks my livestock
	I will kill the next HE that appears on my property

All statements were rated on a 1–5 Likert scale by interviewees (from 1 for highly agree to 5 for highly disagree).

Statistical analysis

We used a null-model approach for all comparisons between persecution events, whether they had been preceded or not by a reported livestock predation event. We chose this approach to avoid bias in our results because of differences in sample sizes between farmers who killed harpy eagles in response to reported livestock predation and those who killed eagles for other reasons (Gotelli & Entsminger, 2006). Our null model consisted of the following steps: (1) bootstrapping one set of samples of landowners that had been affected by livestock predation, and another set of samples for those who had not; (2) calculating the median or the mean for each group; (3) creating a pairwise comparison of medians or means between landowners who lost livestock and those who did not; and (4) determining if the difference in those medians or means found between landowners who lost livestock and those who did not was larger than expected by chance, by comparing differences between two randomly labelled bootstrapped sets of samples. While bootstrapping sets of samples for each simulation, we used the sample size of the smallest group (preceded by reported livestock predation). We carried out 1000 iterations to calculate medians and means differences between different landowner groups, and an additional 1000 were carried to see how far it was from random. We used the median of the Likert scale grading for all cases – since it is an ordinal value – except for comparing other traits for which the mean could be used (e.g. property size). Given that these are ordinal data, we did not calculate a mean or standard deviation value and built our null models using medians and standard errors instead, following Jamieson (2004).

The effects of different independent variables related to the subjective norm or perceived behavioural control over the statement '*I will kill the next harpy that appears on my property*' were tested using ordinal logistic regressions (OLRs). This approach allowed us to use the ordinal 1–5 Likert scale responses in a statistically meaningful way (Jamieson, 2004). We, therefore, analysed perceptions about risk offered to livestock and to people against the statement '*I will kill the next harpy that appears on my property*' to test hypotheses I and II respectively. We analysed the occurrence of previous livestock predation events (hypothesis III) against the statement '*I will kill the next harpy that appears on my property*'. We also analysed the perceptions of family and neighbours opinions concerning harpy eagle killings, as well as the behavioural control perception of impunity against the outcome '*I will kill the next harpy that appears on my property*' to test hypothesis IV. We considered property size (in hectares) against the statement '*I will kill the next harpy that appears on my property*' to test hypothesis V. Finally, we analysed livestock abundance (numbers of head), proximity to nearest forest (in metres) and level of livestock management (LHI) against the Likert grade of the statement '*I will kill the next harpy that appears on my property*'. Normal distributions for each test were derived from the original data.

In examining the drivers explaining local intentions regarding local intentions to kill additional harpy eagles, we also used an OLG-based Akaike Information Criterion (AIC) test, with the following covariates (Pearson's value >0.6, considered to be non-collinear): Likert grade for the statement '*If I kill a harpy eagle on my property it is my problem*' as a measure of perceived behavioural control, property size (ha) as a proxy for financial wealth, previous occurrence of livestock predation by harpy eagles in the property (0 or 1), and the Likert Scale results regarding local perception of harpy eagles as a threat to both humans and livestock. We ran another OLR-based AIC to predict the intention to kill additional harpy eagles exclusively across those interviewees who had lost livestock, with the same criteria for non-collinear covariates, including proportion of livestock killed (%), livestock species killed as a categorical variable (when more than one species had been killed, we used the species taken most frequently) and property size (as a proxy of wealth). In both AICs, the response variable was the Likert grade of the statement '*I will kill the next harpy that appears on my property*'. AIC estimates prediction error (Crawley, 2007) and consequently can test the quality of different statistical models for different datasets (Gotelli & Ellison, 2013).

We conducted all analyses and produced all figures in the R coding environment, version 4.0.3 (R Core, 2020). R packages used were *FSA*, *plyr*, *foreign*, *ggplot2*, *MASS*, *Hmisc*, *reshape2*, *scales*, *RColorBrewer*, *dplyr*, *ggthemes* and *stringr* (Wickham, 2011, 2012; Ripley *et al*., 2013; Neuwirth, 2014; Harrell Jr & Harrell Jr, 2015; Wickham *et al*., 2015; Arnold, 2017; Ogle, 2017; Strong, 2019; Wickham & Wickham, 2019; Bivand *et al*., 2020; Wickham & Wickham, 2020).

Results

Harpy eagle persecution

Collectively, a total of 181 harpy eagles were killed over a 2-year period by the 184 local livestock owners we interviewed within a combined property area of 349 800 ha. This represents an annual killing rate of 2.59 individuals/100 km². Only 19.5% (n = 36) of all attempted or successful killings responded to self-reported livestock predation. Of those 36 events, five (13.8%) failed in killing the eagle, 29 (80.5%) killed one eagle and two (5.5%) killed two eagles. Another 148 (80.5%) individual harpy eagle killings were entirely unrelated to livestock predation. The eagle carcass was consumed in only 4.4% of all occasions and either discarded entirely or kept as relics (mostly the exceptionally large talon) in 74.5% and 21.2% of occasions respectively. Residents who killed harpy eagles were mostly migrant ranchers from southern Brazil, with only 5.4% born in Mato Grosso.

Ranchers who reported livestock depredation by harpy eagles typically had smaller properties (1062 ± 5344 ha) than those who did not report depredation (2104 ± 1516 ha), but this difference was not significant (Null model, P = 0.077). However, after removing two outlier landholdings of 4000 ha and 32 000 ha from the self-reported livestock predation group because of peculiarities they shared, these differences increased (65 ± 81 ha vs. 2104 ± 1516 ha) rendering the null model significant (P < 0.01). Ranchers who reported livestock losses to eagles typically had their habitation and infrastructure (and consequently their small livestock) nearer forest edges (mean distance to the forest = 62 ± 74 m). All variables describing ranches that suffered harpy eagle predation are detailed in Table 2.

Local perceptions

Cronbach's alpha was high (0.769), denoting high consistency in the data. The 95% confidence interval based on

Table 2 Summary characteristics of the surveyed cattle ranch landholdings in terms of management and productivity of livestock in the present study

Ranch characteristics	Mean	SD±	Range	N
Ranch size (hectares)[a]	65.64	81.48	20–500	36
Residency (years)	16.1	6.48	2–30	36
Number of livestock attacked (~2014)	2.87	2.83	1–15	33
Number of livestock attacked (~2015)	3.23	2.67	1–12	30
Distance to the nearest forest area (m)	62.16	74.39	0–400	36
Number of livestock per ranch (head)[b]	49	27.79	13–135	36
Number of pets per ranch	4	1.45	1–8	36

[a] Two properties of 32 000 and 4000 hectares were excluded as outliers.
[b] Cattle not included.

Table 3 Differences in a Likert scale (median ± SE) for people who had killed harpy eagles (HEs) with or without self-reported livestock predation incidents, examined using null models

Statement	With livestock predation (n = 36)	Without livestock predation (n = 148)	P value
The HE is a threat to livestock	2 ± 0.14	3 ± 0.12	0.331
The HE is a threat to humans	2 ± 0.26	4 ± 0.05	<0.01
In this property, we cannot tolerate HEs attacking livestock	3	–	–
My neighbours approve killing HEs attacking livestock	2 ± 0.26	4 ± 0.08	<0.01
My family approves of killing HEs attacking livestock	2 ± 0.21	3 ± 0.08	0.141
My neighbours kill HEs that attacks livestock	1 ± 0.11	4 ± 0.08	<0.01
My neighbours are my friends	2 ± 0.12	4 ± 0.9	<0.01
If I kill a HE on my property, it is my problem	2 ± 0.15	2 ± 0.07	1
I will kill the next HE that attacks my livestock	3	–	–
I will kill the next HE that appears on my property	2.78 ± 1.26	4.09 ± 1.18	<0.01
HEs attacking livestock is an acceptable problem	1	–	–
I would be very happy if there were no HEs	3 ± 0.20	5 ± 0.05	<0.01
HEs need to be protected	3 ± 0.16	5 ± 0.04	<0.01
The government must be held responsible for the HE problem	3	–	–
Each property should solve its own livestock predation problem	1	–	–
I would like help to solve the livestock predation issue	4	–	–
The Amazon is adequately protected	4 ± 0.10	4 ± 0.08	1
I consider myself aware of the conservation problems in the Amazon	3 ± 0.13	4 ± 0.08	0.305

Values close to 5 indicate high disagreement with the statement, while values close to 1 indicate high agreement.

1000 iterations ranged from 0.706 to 0.811. Several traits quantified by the Likert scale yielded significant differences between locals who killed eagles in response to self-reported livestock predation and those who did not (Table 3). People who reported livestock predation were more likely to believe that: (1) harpy eagles were a threat to humans ($P < 0.01$); (2) their neighbours also killed harpy eagles preying on livestock and approved of those who did so ($P < 0.01$); (3) the neighbours were their friends ($P < 0.01$); (4) planned to kill the next eagle that appeared on their property ($P < 0.01$); (5) would be happier if there were no harpy eagles ($P < 0.01$) and (6) perceived little need for harpy eagle protection ($P < 0.01$).

Regarding the likelihood of killing a harpy eagle in the future, perceptions regarding the threat eagles pose to livestock or humans were irrelevant. Prior experience with livestock predation was the single most important factor (hypothesis III; OLR, $\chi^2 = 0.9942$, Residual Deviance: 505, livestock predation $P = 0.006$). Perceptions regarding the threat to livestock (hypothesis I; $P = 0.981$) or threat to humans (hypothesis II; $P = 0.915$) were both non-significant. Therefore, we rejected Hypotheses I and II because those who perceived that livestock or humans were threatened by harpy eagles were less likely to kill them than those who actually lost livestock to harpy predation in the past.

For hypothesis IV, no variables related to the subjective norm (opinions of family and neighbours) and the perceived behavioural control (perception of impunity) had any influence on the likelihood of someone killing harpy eagles (OLR, $\chi^2 = 0$, Residual Deviance: 501, $P > 0.05$ for all variables). We, therefore, rejected Hypothesis IV, as neither perceptions over subjective norms nor behavioural control were important in predicting harpy eagle killings.

Contrary to hypothesis V, property size exerted a strong negative effect on the intention to kill harpy eagles (OLR, $\chi^2 = 0.40624$, Residual Deviance: 519, $P < 0.01$). Consequently, smallholders had the most hostile profile regarding their clear intentions to kill harpy eagles in the future, whereas large holders were most tolerant and likely to spare eagles (Fig. 3).

A total of 31 models incorporating all possible combinations of the four covariates were analysed against the Likert grade for '*I will kill the next harpy eagle that appears on my property*'. The top model (lowest AIC, Table 4) incorporated property size (ΔAIC = 0, 172 DF) and one or more previous livestock predation event. While increasing property size makes further harpy eagle killings less likely, previous occurrence of livestock predation had a positive effect. The second lowest AIC model (ΔAIC = 0.8, 176 DF) had a negative effect on the Likert grade of the statement '*If I kill a*

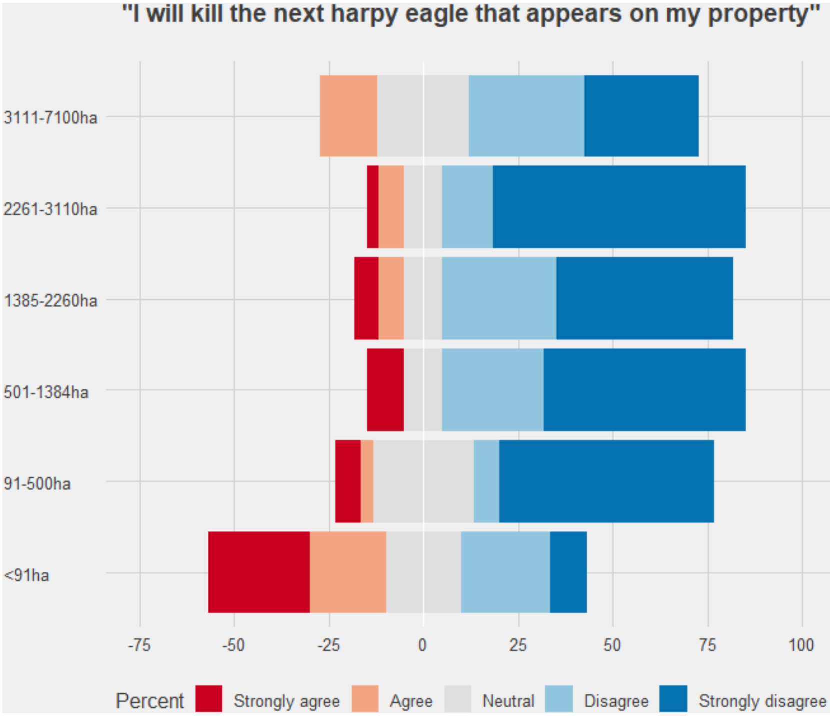

Figure 3 Summary of intention to kill harpy eagles along a gradient of property sizes. Each category has a sample size of ~30 properties. Intent to kill harpy eagles in the future were most prevalent among smallholders.

Table 4 Results of the model selection to analyse the probability with which an interviewee will kill the next harpy eagle that enters its property

Variables	Residual DF	RD	AIC	ΔAIC	Weight
var1 + var2 + var3	172	472.27	492.27	0	0.39
var2 + var3	176	481.12	493.12	0.8	0.25
var1 + var2 + var3 + var4	168	466.95	494.95	2.7	0.10
var2 + var3 + var4	172	475.62	495.62	3.4	0.07
var1 + var3	173	477.81	495.81	3.5	0.07
var3	177	486.40	496.40	4.1	0.05
var1 + var3 + var4	169	472.36	498.36	6.1	0.02

Variables, residual degrees of freedom (DF), residual deviance (RD), Akaike's Information Criterion (AIC) value and the difference in AIC between the model with the lowest AIC and a given model (ΔAIC) and Akaike weights for ordinal logistic regression are shown. The var1 stands for 'If I kill a harpy eagle on my property it is my problem', var2 for landholding size, var3 for previous livestock predation, var4 for 'The harpy eagle is a threat to livestock' and var5 for 'The harpy eagle is a threat to humans'. Perception of behavioural control (var1), together with landholding size (var2) and previous livestock predation (var3) yielded the most parsimonious models with a positive relationship with the Likert grade for the statement 'I will kill the next harpy eagle that appears on my property'.

harpy eagle on my property, it is my problem', together with the two variables mentioned in the previous model with the same effects. However, both models had low weights (of 0.39 and 0.25 respectively), revealing a low explanatory capacity for each model.

For the AIC regarding the levels of livestock predation and intentions of killing further eagles, we had a total of seven models for all possible combinations (Table 5). The top model (ΔAIC = 0, 25 DF) included the proportion of livestock killed, where greater proportions correlated with stronger intentions to kill further eagles, and livestock species killed, with higher grades of intention to kill harpy eagles for those who lost pets (dogs and cats) to harpy eagle predation, followed by those who lost domestic ungulates, and then chickens. The second lowest AIC model (ΔAIC = 0.9, 29 DF) had a single variable, namely the proportion of livestock killed, resulting in further hostility towards eagles. As in the previous batch of analyses, even

Table 5 Results of AIC model selection to analyse the effect of the levels of livestock predation on the intentions of killing further eagles

Variables	Residual DF	RD	AIC	ΔAIC	Weight
var1 + var2	25	92.83	110.83	0	0.30
var1	29	101.76	111.76	0.9	0.19
var2	26	95.90	111.90	1.1	0.18
var1 + var2 + var3	24	92.78	112.78	1.9	0.11
var3	29	103.58	113.58	2.7	0.08
var1 + var3	28	101.65	113.65	2.8	0.07
var2 + var3	25	95.90	113.90	3.1	0.07

Variables, residual degrees of freedom (DF), residual deviance (RD.), Akaike's Information Criterion (AIC) value and the difference in AIC between the model with the lowest AIC and a given model (ΔAIC) and Akaike weights for ordinal logistic regression are shown. The var1 stands for the proportion of livestock killed, var2 for livestock species killed and var3 for landholding size. The proportion of livestock killed and the species killed were in the most parsimonious model, with a positive correlation with the intention to kill harpy eagles in the future.

the models with low values for ΔAIC had a limited explanation potential, with weights of 0.30 and 0.19.

Livestock predation

Livestock abundance and less intensive livestock management had positive effects on domestic animal predation rates by harpy eagles (hypothesis VI), and did so significantly (GLM, Residual deviance: 52.47, d.f. = 32, $P < 0.01$ for livestock abundance and $P = 0.0157$ for livestock management). Distance to the nearest forest patch (range: 0–400 m, $P = 0.10$) had no effect (Fig. 4). Domestic livestock species reported by interviewees as preyed upon by harpy eagles are summarized in Table 6. Monetary losses resulting from harpy eagle predation were relatively low: the annual value

Table 6 Livestock species reported by landowners as being preyed on by harpy eagles in small ranches

Species	%	N	Value (US $)	Observations
Chicken (*Gallus gallus*)	47.9	92	343.39	Preference for roosters
Goat (*Capra hircus*)	22.4	43	380.08	
Pig (*Sus domesticus*)	18.2	35	30.56	
Sheep (*Ovis aries*)	8.3	16	121.73	
Dog (*Canis familiaris*)	2.1	4	–	Small-sized sick adult
Cat (*Felis catus*)	1.0	2	–	
			437.89	Yearly total

While cattle ranching is the main non-forest economic activity in Brazilian Amazonia, harpy eagles do not prey on cattle but do so on a wide variety of smaller livestock. Values refer to 2 years of predation records, and monetary loss was calculated based on average losses per year.

of all livestock kills across all 36 landholdings averaged US $438/year throughout our study region, and only a small number of livestock were taken from each property (3.05 head/property). This represents only US$12.2/year per property or US$1.1/km²/year considering properties with documented attacks or US$0.1/km²/year if we consider our entire study region.

Discussion

Here, we have shown that previous occurrence of livestock predation played a small role in harpy eagle killings in the wider Amazonian landscape and was related to fewer than 20% of the cases reported by interviewees. Most killings in our study region were typically out of curiosity, misconception or both. These were unrelated to both the subjective norm and perceived behavioural control. Therefore, the

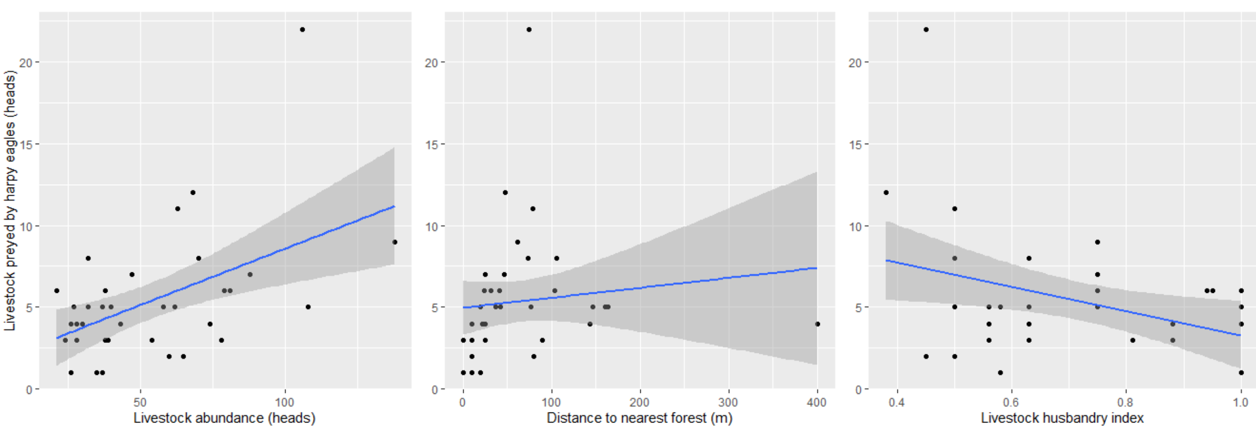

Figure 4 Respective effects of livestock abundance, distance to the nearest forest patch area and livestock husbandry index (LHI) vs. the number of individual livestock killed by harpy eagles. Although all of these relationships are positive, only livestock abundance had a statistically significant effect.

Planned Behaviour Theory failed to explain our observations. Additionally, the intention to kill harpy eagles in the future appeared to be associated with (1) land property size, being stronger in smallholdings and (2) self-reported occurrence of livestock predation, inducing intentions to kill harpy eagles further. This occurred independently of perceptions concerning the risk harpy eagles may potentially present to humans or livestock. Failing to consider conflict destabilizes conservation efforts and thus prevents meaningful impacts on conservation policy and erodes local community support for such conservation efforts (Widdows & Downs, 2018; Zuluaga *et al*., 2020). The extent and nature of harpy eagle killings must be central to the conservation of this apex predator since, even if local perceptions of livestock predation are exaggerated, the issue must be addressed proactively and based on evidence.

The overall killing rate of 2.59 harpy eagles per 100 km²/year is a critical finding for the population viability of this mega-raptor. Published harpy eagle densities report 12 breeding adults/100 km² in high-density areas (González & Vargas, 2011), and each pair produces a single eaglet every 30–36 months (Muñiz-López *et al*., 2012; Muñiz-López, 2017). This eaglet will then take 2–3 more years to reach sexual maturity (Oliveira, 2019). Given their prolonged life history, even for a large raptor, harpy eagles cannot persist under sustained killing rates as high as those reported in this study. This, combined with the ongoing extensive forest loss across the Amazonian Arc of Deforestation (Sutton *et al*., 2020), makes conservation management of harpy eagles critical for their persistence wherever they co-exist with humans.

The rationale of killing an animal without purpose (e.g. in retaliation for livestock predation) may sound strange – especially to foreigners – but the feeling of ‘hand-experiencing’ something is common in Brazilian culture and has even resulted in popular Brazilian Portuguese expression: ‘to see with the hands’ (Rosumek, Schmiegelow & de Sousa, 2018). Research shows that touching an object results in an increase in perceived ownership (Peck & Shu, 2009), and we believe this is one of the main issues behind many of the harpy eagle killings. Furthermore, rural people in Brazil frequently own illegal guns. Finally, a specific vulnerability trait of harpy eagles is that they often remain perched for several hours in the same emergent tree, allowing a rural rancher enough time to go home, and fetch his gun to ‘investigate’ the huge raptor.

Searching for social cues to change behaviour and reduce harpy eagle killings seems a very straightforward process. We established a tourism initiative that relies on locals to (1) find nests under a US$100 reward; (2) assemble ecotourism observation towers and (3) act as a paid workforce for many associated tasks (Miranda *et al*., 2021*a*), besides offering US $20 per tourist per day to the landowner. Perception of risks and benefits are primary factors regarding tolerance of apex predators (Bruskotter & Wilson, 2014), and we are introducing the benefits. Since people perceived mild risk in regards to harpy eagles (except for the minority of landholders who lost livestock), we made an effort to publicize the tangible tourism benefits accrued by this species (Miranda *et al*., 2021*a*) starting a year after the interviews. Furthermore, our initiative offers concrete economic benefits that permeate through the community via local restaurants, lodges, car rental companies and so on, as is typical for ecotourism (Kirkby *et al*., 2010). Although we paused the program offering rewards for new nests in February 2020 (given limitations imposed by the COVID-19 pandemic), we still received information on six new nests from February to December 2020. In conclusion, these results suggest that ecotourism benefits can induce changes in the local peoples’ complex perceptions of harpy eagles, as extolled by conservation marketing initiatives (Wright *et al*., 2015).

Predator persecution in the complete absence of human–predator conflicts is not unheard of (Knox *et al*., 2019). However, the problem is usually the perceived threat posed to humans. For harpy eagles, local beliefs that they could prey on small children were typically held by those who lost livestock to eagles. Complete prevention of further predation events would be difficult to implement because of the various measures required to protect different domestic livestock types. Furthermore, the yearly value of livestock prey was relatively low and generally affordable in our study region (<US$500/year or US$12.2/year per property), with a small number of livestock removed per property (<4 head/property). In other words, this can be easily matched by a compensation program derived from ecotourism revenues since Brazil has no state-sponsored compensation system (Ravenelle & Nyhus, 2017).

The higher rates of reported livestock predation by harpy eagles in smallholdings were likely related to the fact that their habitation and homestead infrastructure were frequently located near the borders of forest patches. Smallholders typically have their houses near perennial streams to facilitate access to the water. Small livestock are consequently more exposed to forest predators. Notably, the two estates reporting livestock predation, which we removed from the analysis as outliers (4000 ha and 32 000 ha), were dedicated to selective timber extraction, with their offices and housing located on the forest margin (EBPM, pers. obs.). Large- and medium-sized landowners carried out most reported harpy eagle killings in this study. We suggest that smallholders are responsible for most of the harpy eagle mortality. This apparent contradiction is caused by the fact that smallholders in northern Mato Grosso greatly outnumber larger estates at a ratio of 50:1 (Michalski, Metzger & Peres, 2010; Godar *et al*., 2014). Smallholders represented the only group that declared consistent intentions to kill more eagles in retaliation for previous predation events. In contrast, estate owners frequently reported that they killed eagles out of curiosity and admiration and generally declared later regretting their actions. The large proportion of large holders who declared no intention to kill further harpy eagles confirmed that large holders are unlikely to be the main source of mortality.

Opportunities and challenges involving apex predator conservation within private landholdings are typically governed by the economies of scale of such properties, which is primarily a function of property area (Michalski *et al*., 2006; Silva *et al*., 2018). In rejecting our Hypotheses I and II (regarding the threat to humans and livestock), we established that conservation programs should focus on those who had lost livestock to harpy eagles (smallholders). High rates of harpy eagle killings shown by rejecting Hypothesis V (perceived behavioural control increases with landholding size, and so does harpy eagle killing) is further evidence to add to a complex mix of environmental issues induced by agrarian reform-based distribution of small landholdings in Amazonia. This further results in higher levels of riparian forest degradation (Zimbres, Machado & Peres, 2018), as smallholders typically convert a higher proportion of their properties from forest to agropastoral land cover (Schneider & Peres, 2015).

Harpy eagles are typically poor long-distance fliers with short and round wings (Ferguson-Lees & Christie, 2001). Indeed, they rarely cross non-forest areas wider than 500 m (Aguiar-Silva, 2016). Harpy eagles typically use a 'sit-and-wait' hunting strategy (Touchton, Hsu & Palleroni, 2002), and this has led them to be restricted to attacking domestic livestock close to forest. Miranda *et al*. (2018) showed that male harpy eagles prey five times more frequently on terrestrial prey than females (11% vs. 2% of prey composition). The smaller bodied males are also more generalist. Such characteristics mean livestock predation is likely to be typical of male harpy eagles. This could lead to biased mortality towards males, with severe consequences to the population demography (Alvarez-Cordero, 1996).

It is interesting to note that low levels of livestock predation – or the lack thereof – have been reported for other eagles, such as the crowned solitary eagle (*Urubitinga coronata*; Sarasola, Santillán & Galmes, 2010) or the crowned eagle (*Stephanoaetus coronatus*; McPherson, Brown & Downs, 2016). Furthermore, most interviewees did not consider harpy eagles to be livestock predators. Cattle ranchers in the Arc of Deforestation confront other livestock predators (large felids and boid snakes) on a day-to-day basis. Conversely, harpy eagles occur at low densities and hardly ever prey on terrestrial vertebrates or livestock (Miranda *et al*., 2021*b*), leading local people not to consider them a significant threat to livestock as the other, omnipresent, terrestrial predators.

In conclusion, the patterns of harpy eagle killing profiles and landowner perceptions we reveal here are important in designing, managing and funding conservation activities for harpy eagles and other large Amazonian predator species. Livestock predation by harpy eagles was typically uncommon, and killings were not normally directly related to the mortality of domestic animals. Self-reported livestock predation in the past was, however, a strong predictor of further intentions to kill harpy eagles. Smallholders were most likely to inflict this mortality, and as they are the dominant class of landowners, they should be the focus of education and compensation schemes to address undesirable killings. Since respect for harpy eagles was commonly reported by larger landowners, they may also benefit from educational activities as they have the most to offer to forest wildlife in terms of extensive areas of remaining habitat. As a result, our determination of the profiles and drivers of landowners persecuting harpy eagles provides a baseline to understand continued harpy eagle persecution, elucidating how and where to start working to reduce it.

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Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Geographic and demographic information about the human and livestock population in the counties we sampled in Northern Mato Grosso, southern Amazonia, Brazil.