Final Evaluation Report

Your Details	
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Project Title	Building a conservation strategy for the Harpy Eagle in the Amazon Forest
Application ID	23022-2
Grant Amount	£5000
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Date of this Report	December 2018

1. Indicate the level of achievement of the project's original objectives and include any relevant comments on factors affecting this.

Objective	Not achieved	Partially achieved	Fully achieved	Comments
To collect fine-grained data on Harpy Eagle feeding ecology and see how their foraging dynamics are related to landscape features. Consequently, we will be able to predict and thus prevent the predation of domestic animals.				Through the last year we have gathered around 40 gigabytes of imagery from the 10 nests in which we already concluded our sampling. This effort has yielded a few hundred prey records that, combined with the bone collection at and beneath the nests, will soon allow us to build an unprecedented data set of the prey composition of harpy eagles (see attachment I). Currently, the student Nickolas Lormand (New Mexico State University) is working on the effects of landscape anthropisation over harpy eagle dietary traits. Finally, our results proved to be of little help regarding domestic animal predation. No nesting eagle has been shown to prey on domestic livestock, even though we are aware of cases where eagles – from nests we do not know – forage nearby homesteads and eat domestic animals. Regardless, we have been trying to address domestic animal predation by offering compensation payments to locals who reliably claim to lose livestock to eagles. Unfortunately, this kind of action is more limited than we would like and, in several cases, eagles have been killed in retaliation for domestic animal predation.
To test if our network of nut collectors can help us to reach a critical mass of active, accessible, protected nests that would then attract major investments in				That has surely been our most important step up until now. The partnership with the tourism company has rendered our project more constant funds, avoiding months of abundance interchanged with "donor fatigue". Furthermore, those resources are not attached to specific aims, so they perfectly fit our unpredictable demands. Please see also:

sustainable tourism.				https://www.youtube.com/watch?v=9Rg8LxUnFvU http://www.southwild.com/harpy-eagle-guaranteed/ Furthermore, we have been able to inject more funds into local communities through tourism, in addition to the rewards for finding nests and the compensation for livestock killed by eagles. This was done by locals hired to build towers, carry heavy material into the field, drive cars and boats, clean the trails and cook at the camps. This has a clear role in turning the "economically sterile" forests into a source of wealth to locals. We have achieved a benchmark of 100 nest visits this year, working on two nests, and hope to expand to 200 in 2019.
To compare indicators of: a) the income of local families; b) number of livestock killed; c) number of eagles killed at the beginning of the project versus number killed after methods of predation avoidance and ecotourism were implemented.				Unfortunately, there is little spatial overlap – if any – between the sites where we have been working with tourism and the ones presenting problems with livestock predation. While it is economically and logistically simple to direct resources from sites that are producing money from tourism to the ones that need them for compensation, it should take tourism several years (perhaps 5-10) to be widespread enough to affect people's income and opinion at a landscape scale. As happened in Pantanal for jaguars, we are sure that time will bring other entrepreneurs and small-scale tourism companies following similar business models, protecting more harpy eagles and their habitat.
To publish scientific results of prey composition (with emphasis on livestock killed) and its relationship with different land uses. To create cheap, simple methods to avoid livestock predation.				As commented before, prey composition results are currently being handled by Nickolas Lormand, which after an internship with our team decided to pursue this subject as part of his Master's thesis. Whereas the creation of a predator avoidance manual for locals has been my dream since the start of this initiative, now it is clear that the main predictor for harpy eagle attacks to livestock is the presence of tall trees nearby homesteads. This is an

				interesting phenomenon since these trees are virtually all Brazil nuts, a species that is protected by law in Brazil and that usually stands alone in formerly forested pastures. As recommending locals to cut threatened trees is far from our aims, we will remain dealing with this problem by paying compensation to locals and spreading the message that this kind of reward is available.
To publish guidelines for ecotourism management and predation avoidance in Portuguese.				First advances on the ecotourism subject have been made by the student Niki Huizinga. She has analysed the activity patterns of eagles with views to practical applications in tourism, and her graduation thesis can be seen in the attached material. Please see attachment II for details. The publication of detailed instructions regarding tourism will need to wait until our operation matures as harpy eagles are a new product in the industry, the operations here have not been lucrative up till now and we would not be able to financially tolerate competition at the present, whereas we consider that this competition will generate positive results in the future. The reasons why we are not pursuing the creation of a manual on predation avoidance anymore is described on the previous section.
To extensively advertise our reward program for anyone able to show us an active Harpy Eagle nest. We are offering US$160 per nest (2/3 of a monthly salary in this region). With a critical mass of 10-15 active nests, 3-5 should always be in the activity phases that allow effective photo safari tourism.				We have found more nests than expected and are currently breaching the 20 nests barrier. Now we aim to reach 50 on the next few years in order to constantly have at least one nest with a small chick – whereas adult harpy eagles can already be reliably seen. Additionally, we found our first nest in the southern landscape of Mato Grosso state. Specifically in the region were the Cerrado, the Amazon forest and the Pantanal meet. This is amazing since the place is a few hours by car from "jaguar capital", having enormous potential for tourism and for further launching the harpy eagle as a new attraction in the market. Since the region is more than a

				1000 km away from our current study site, we are selecting a new PhD student to work on searching new nests. Please see attachment III in Portuguese.
To approach leading Brazilian and international ecotourism companies to interest them in investing in the conservation and photo tourism of this species.				We have successfully made an alliance with SouthWild.com for this aim, and up till now, the results could not have been any better. Landowners have been happy to sign contracts with us and some who previously denied access of our research team to their properties have changed their minds. Landowners currently are paid $20 per person per day, which means that if a group of five tourists remain at a nest for three days, they are paid $300, a quite sizeable amount for protected private areas that are considered economically sterile.

2. Please explain any unforeseen difficulties that arose during the project and how these were tackled.

I was afraid that for the last year of our project my main challenge would be to combine my work at the university and the field activities related with this project, and consequently my PhD. Nothing could be farther from truth. The university proved to be of great help regarding the project, offering equipment we can use (4WD cars, camera traps, space to store equipment and samples) and legal support (for inviting international students to spend time helping us and providing them with easier ways to obtain visas). It has also provided us with a better "business card", since we now present ourselves as university members and locals have a positive view of the institution.

On the other hand, changes in the UK legislation now strictly forbid foreign students to enrol in part-time PhDs. As a result, I was forced to change to a PhD with more flexible rules that could accommodate my fieldwork demands and my schedule at the university, and I chose South Africa for this. This was by far the biggest problem of 2018, requiring me to spend a lot of time in bureaucracy again and severely delaying the publication of several papers that will be part of my thesis.

In addition, harpy eagles continue to be killed for preying livestock along the arc of deforestation. It will take years for our compensation efforts to arrive at the farthest corners of our state, and killed eagles or their body parts still arrive at our hands from time to time. Fortunately, at least for one of those cases, we were able to track the perpetrators and bring this information to local authorities, which took the appropriate legal measures. Please be aware that the videos below show disturbing images:

https://www.youtube.com/watch?v=g-wyImIErG8 https://www.youtube.com/watch?v=eEXimZ_IYyU&index=5&list=UUY08PGPg-J0gxbsv-wEGyKg

A final unexpected problem took over our team in January 2019. A fledged eagle was wounded by it's prey, and trying to capture and take it to veterinarian care consumed an awful amount of resources and time from our team. Those resources could certainly be used to protect and study many other nests but it is hard to condemn a single individual for taking better care of a population. The images of this individual can be seen in the last page of Attachment I. Unfortunately it died on February 4th 2019.

3. Briefly describe the three most important outcomes of your project.

- Finding and protecting 20 harpy eagle nests in the arc of deforestation, the main agricultural expansion frontier of earth.
- Building a functional and solid alliance between research, conservation and tourism, with shares for all stakeholders.
- Building for the first time a distribution model for harpy eagles. We delineated for the first time the plausible, global-scale distribution of earth's largest extant eagle, which is of prime management and conservation interest. Between the main discoveries is that eagle distribution has retracted 41% when compared with what is IUCN current estimate, and that there is a huge habitat patch in the Atlantic Forest that could support reintroductions. Please see attachment IV for this paper.

4. Briefly describe the involvement of local communities and how they have benefitted from the project.

Locals continue to be paid by each nest found, besides receiving compensation for domestic livestock killed by eagles. In addition, they have been hired to work with us in several functions, such as to build towers and platforms, drive cars and boats, open trails, as assistant tourism guides, porters of gear, etc. On top of that, landowners are currently paid for each visiting tourist. Finally, we emphasise all the positive side effects of our activities, like the increased movements in hotels, restaurants, car fixing shops and more that help locals to see the possible benefits of a green economy.

5. Are there any plans to continue this work?

Absolutely yes, since I started working in the University, I decided that I will live in the arc of deforestation for the rest of my life. So, the research and conservation initiative we started here should last a lifetime. The only thing that may change in the next few years is that I plan to expand my research initiatives to other predators such as jaguars and anacondas.

6. How do you plan to share the results of your work with others?

Besides our scientific publications, we have been publishing some articles in Portuguese in popular media outlets, and have been doing school lectures for small children. See below, in Portuguese:
https://www.oeco.org.br/colunas/colunistas-convidados/de-quase-heroi-a-quase-bandido-como-nao-salvar-um-filhote-de-harpia/

7. Timescale: Over what period was the grant used? How does this compare to the anticipated or actual length of the project?

The Rufford grant was essentially used during the rainy season of 2017-2018, in the Alta Floresta region where we desperately needed to find a nest. Most of our nests cannot be shown to tourists in the same day they arrive in the city, and this became an achilles heel for our tourism enterprise and a personal quest for me. By concentrating efforts here from December 2017 to March 2018, we were successful in our search. The resources coming from tourism as well as from Cleveland Metroparks Zoo made up most of the resources used in the last year.

8. Budget: Provide a breakdown of budgeted versus actual expenditure and the reasons for any differences. All figures should be in £ sterling, indicating the local exchange rate used. It is important that you retain the management accounts and all paid invoices relating to the project for at least 2 years as these may be required for inspection at our discretion.

Item	**Budgeted Amount**	**Actual Amount**	**Difference**	**Comments**
Drone	800	100	-700	After some preliminary tests with drones, we noticed they weren't as reliable as we needed for sensing prey or searching for nests. Consequently, we bought a much cheaper model just for checking nests without needing to climb them. The difference was invested in searching for nests in the Alta Floresta region.
Batteries (box)	140	140		
Meals	186	216		
Lodging	605	1080		
Nest reward	628	628		
Camera trap	969	388	-581	We preferred to invest further resources in searching for nests in Alta Floresta region.
Fuel (litres)	450	980		

Driver/boatman per diem	403	649		
Climber per diem	752	752		
TOTAL	**4933**	**4933**		

9. Looking ahead, what do you feel are the important next steps?

- Increase the number of monitored nests.
- Increase the participation of local students from the local universities in the project.
- Publish the data I collected up till now.
- Finish my PhD so that I can include new students on the project.
- Acquire vehicles for the exclusive use of the project.
- Further spreading the message of the availability of a compensation for livestock killed by harpy eagles.

10. Did you use The Rufford Foundation logo in any materials produced in relation to this project? Did the Foundation receive any publicity during the course of your work?

Rufford logo is present in all posters and pamphlets of the project. Furthermore, we used it in all our slideshows in schools and universities.

11. Please provide a full list of all the members of your team and briefly what was their role in the project.

Roberto Stofel: skilled climber. Born on the Arc of Deforestation, helps us to reach the Harpy Eagle nests with unthinkable bravery.

Gilberto Araújo: Driver, boatman. Arrived to this region as a teenager, during the first state-sponsored colonization projects. By being raised here, he became an accomplished 4WD driver and can overcome any quagmire on the often very muddy roads of the region.

Dr. Alexander Blanco: External advisor. Alexander is one of the world's foremost specialists on Harpy Eagles, and frequently advises us on climbing technics, field gear and protocols to access nests.

We have many partner biologists who sometimes work with us as part-time job. These include **Lorena Castilho, Maicon Ferri, Diego Afonso, and Geanice Cristina.** All them came to northern Mato Grosso to work on hydroelectric power dams as biologists and then stayed in the region. Nowadays they help us on the project as freelance biologists.

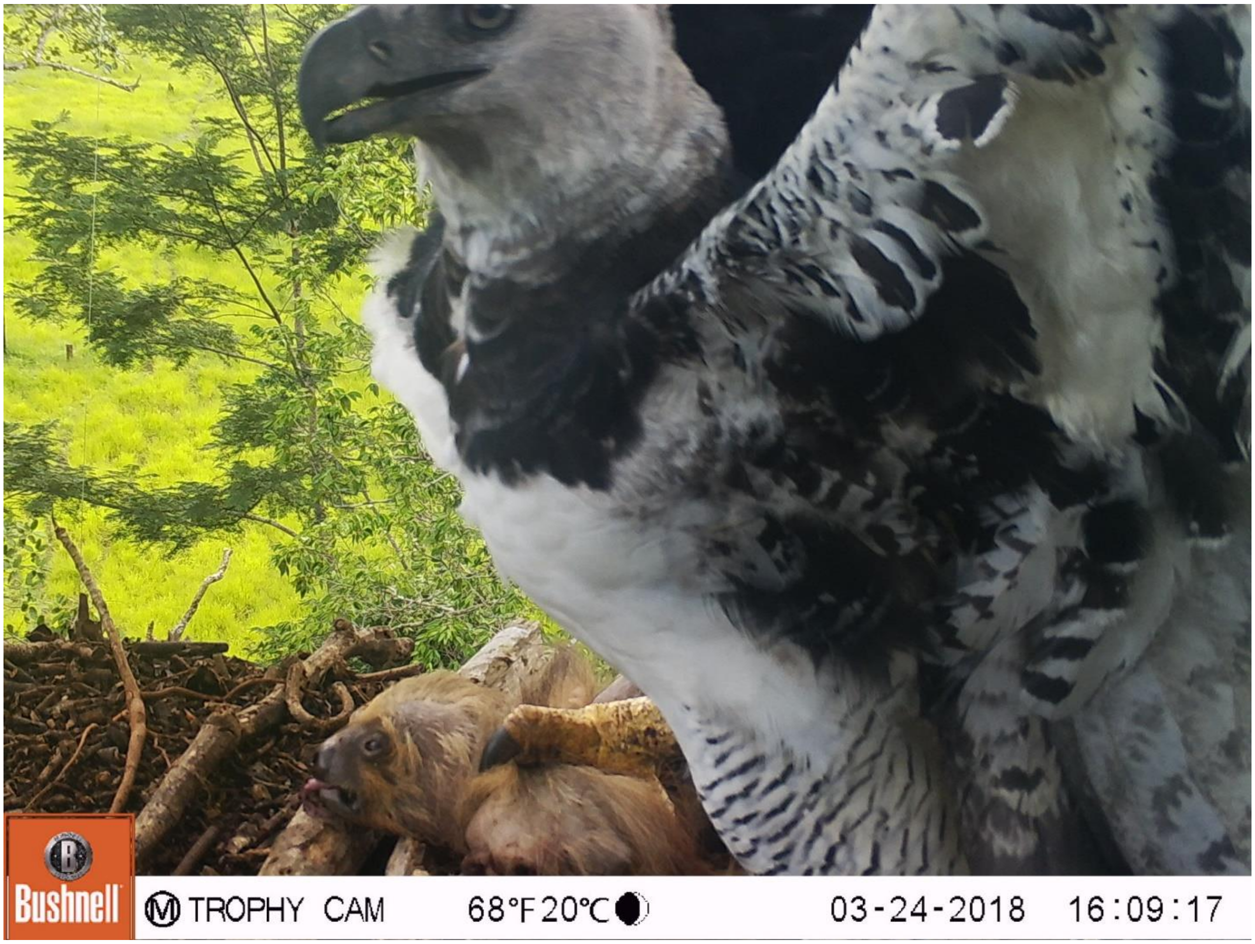
Harpy Eagle chick looks at the camera.

Adult Harpy Eagle feeds on young two-toed sloth.

Male Harpy Eagle arrives at nest with prey.

Young Harpy Eagle practicing flight at nest.

Female Harpy Eagle arrives at nest with a wooly monkey carcass.



Adulto Harpy Eagle arrives at nest with a sloth.


Note the discrete camera trap installing on the nest.


Me climbing a nest to install cameras.


Observation tower installed nearby a nest.

Harpy Eagle preying over razorbilled curassow.


Bushnell
10-18-2018 10:27:22

Young Harpy Eagle feeding over Spider Monkey tail.

Harpy Eagle pair at nest.

Harpy Eagle in the savanna nest.

Harpy Eagle bringing new branches to cover old carcasses.

Harpy eagle bringing armadillo prey in the savanna nest.

Harpy eagle fledged before being mauled by prey.

First image of wounded eagle. This foot was ultimately lost and we are trying to capture that eagle.

Harpy eagle (*Harpia harpyja*) activity profiles on nests: the basis for ecotourism

Niki Huizinga

27-01-2019

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Harpy eagle (*Harpia harpyja*) activity profiles on nests: the basis for ecotourism

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Preface

This research project has been conducted to evaluate the activity pattern of the harpy eagle (*Harpia harpyja*). The aim of the study was to find the best hours for tourists to visit the harpy eagle nests with the highest chance on spotting the harpy eagle in action. This study has been conducted on behalf of ONF Brazil, in collaboration with Prof. Everton Miranda (supervisor) who started the data collection in 2016, Francisco de Assis Nunes (field assistance) and Roberto Stofel (Climber and field assistance). We greatly appreciate the generous financial support of the following donors: Rufford Small Grants Foundation (18743-1 and 23022-2), Rainforest Biodiversity Group, Idea Wild, The Mamont Scholars Program of the Explorer's Club Exploration Fund, Cleveland Metroparks Zoo, and the SouthWild.com Conservation Travel System. This work received major logistical support from the Peugeot-ONF Brasil Carbon Sink Reforestation Project, based at Fazenda São Nicolau in the Municipality of Cotriguaçu, Mato Grosso, Brazil. This ambitious project is an outstanding initiative of Peugeot Auto Maker to fulfill directives of the Kyoto Protocol.

Niki Huizinga

Cotriguaçu, January 2019

Abstract

The harpy eagle (*Harpia harpyja*) is listed as 'Near Threatened' but is still dealing with human-wildlife conflicts like logging, poaching and deforestation. Those conflicts can possibly be resolved by wildlife tourism, since wildlife tourism can help mitigating the economic damage caused by harpy eagles and by producing more green jobs. To promote wildlife tourism, it is important to improve the chance of spotting harpy eagles in specific behaviour. This can be obtained by finding a timeframe with the highest chance on spotting the harpy eagle at its nest. The activity of the harpy eagle at its nest was monitored using camera traps. The results of the harpy eagle's circadian activity pattern show that they are most active between 3 and 5 PM. According to those results, this would be the best time for tourists to visit the nests. If wildlife tourism focussed on the harpy eagle would become more active, the effect of the presence of tourists on the harpy eagle should be studied.

Contents

1. Introduction

The Amazon is the largest tropical forest in de world and holds at least 10% of the world's known biodiversity (WWF, 2017). Only 6,3% of the landscape is protected by law and many parks are protected but experience poor or no management (Costa, Leite, Menes, & Ditchfield, 2005). In this environment, several top predators as jaguars (*Panthera onca*), anacondas (*Eunectes murinus*) and harpy eagles (*Harpia harpyja*) play the role of top-down control over trophic cascades (Terborgh et al., 2001).

Approximately 90% of harpy eagle's actual global distribution is in the Amazon rainforest (Miranda, Menezes, Farias, Munn, & Peres, in press). The harpy eagle controls the population of its prey species, mainly sloths and primates (Palomares et al., 1995; Aguiar-Silva et al., 2014; Aguiar-Silva et al., 2015; Miranda, 2015). This way the harpy eagle helps to control the balance in the ecosystem by preventing overpopulation which can lead to damage of the lower trophic levels (Terborgh & Estes, 2010). Harpy eagles are listed as 'Near Threatened' (IUCN, 2017) and have a nest density of 3-6 nests per 100 km^2 (De J. Vargas González & Vargas, 2011). Their population is expected to decline (IUCN, 2017) mainly due to human-wildlife conflicts like illegal logging, deforestation and poaching (Alvarez-Cordero, 1996; Curti & Valdez, 2009; Trinca et al., 2008). Logging removes these trees harpy eagles use to nest in (Da Luz, 2005) and deforestation (when forest gives space to agriculture) results in habitat loss and degradation (Da Luz, 2005; Negrões et al., 2010). The consequential diminution of natural prey can cause harpy eagles to take livestock located nearby deforestation frontiers as their prey (Michalski et al., 2006; Peña-Mondragón et al., 2015; Odden, Nilsen, & Linnell, 2013). Subsequently, cattle ranchers hire professional poachers to kill predators, like harpy eagles (Treves & Karanth, 2003).

As with many top predators, conservation measures are expensive and lack popular support. To advance on conservation for the harpy eagle, it is important to prevent and mitigate the economic damage caused by harpy eagles through livestock depredation (Woodroffe & Frank, 2005). Wildlife tourism has been on the rise in the recent years and it is considered a possible financial support for conservation, including compensation for livestock predation (Tisdell, 2012; Tortato et al., 2017). To achieve this, it is important that the financial revenues from wildlife tourism are higher than the financial damage caused by livestock depredation (Tortato, Izzo, Hoogesteijn, & Peres, 2017). Besides the fact that proper wildlife tourism could lead to conservation it could lead to more green jobs (Sims-Castley, Kerley, Geach, & Langholz, 2005). Green jobs give local people a chance to make a living out of wildlife tourism instead of logging, agriculture or other activities that degrade nature (Lowman, 2009; Kirkby et al., 2010; Kirkby et al., 2011). This way, local people benefit directly from wildlife tourism and become more conscious about wildlife and the environment. This can help predators to be understood and accepted since wildlife and environment will become more valuable to local people (Treves & Karanth, 2003).

Wildlife tourism is based on good experiences from the tourists and should be organized in such a matter that the impact on animals and their habitat are at a minimum. Predictable visibility with daily patterns, or habitat that will increase the activity of the species will attract tourists (Reynolds & Braithwaite, 2001). Also, specific behaviour, like adults taking care of their young, can increase tourists' interest (Skibins, Powell, & Hallo, 2013). The fact that the harpy eagle is a top predator and its conservation therefore affects the whole ecosystem (Trinca, Ferrari, & Lees, 2008), could make the harpy eagle a flagship species for tourism. But since the density of the harpy eagle is low (De J. Vargas González & Vargas, 2011) and its natural behaviour and habits are unknown, this raptor is very difficult to spot (Skibins et al., 2013).

Given the general lack of knowledge on circadian activity patterns of harpy eagles, the high potential for wildlife tourism and subsequently conservation, the primary objective of this study was to describe temporal variability in the visit patterns of harpy eagles to their nests. This will identify the best visiting hours for tourists to spot the harpy eagle. During this study the harpy eagle's activity pattern was analysed using camera traps, to find the peak activity hours of the harpy eagle at its nest.

2. Methods

2.1 Study area

This study spanned 20.000 km^2 and was conducted in the southern Amazon, in the northern part of Mato Grosso, Brazil. This is an area with a tropical climate (Veloso, Rangel-Filho, & Lima, 1991) and the highest rates of deforestation (Roriz, Yanai, & Fearnside, 2017). This region is inhabited mainly by migrants from southern Brazil, with the main economic activity being cattle ranching (Roriz et al., 2017).

Figure 1. Everton Miranda climbing one of the nest trees to check if the cameras are in place. Photo of personal collection.

2.2 Installing camera traps

The Bushnell Trophy Cam Aggressor (specifications of the camera can be found in appendix 1) is a reliable camera fitting the needs of this study. The cameras (including 8 AA batteries and 32GB SDHC memory card) were installed at nine harpy eagle nests, following the tree-climbing protocols as described in literature (Pagel, Thorstrom, 2007; Rosenfield, Grier, Fyfe, 2007). To prevent nest abandonment, installation of the cameras was done at least 15 days after hatching (McPherson, Brown, & Downs, 2015). Two or three cameras were installed at a maximum of two meters from each nest. Monitoring took place 24 hours a day for an average time frame of 109 days per nest. This camera model uses a heat and motion detector and was set to take one photo at each trigger (motion or heat). If the trigger persisted, a new photo was taken every 10 minutes.

Figure 1. Photo of a harpy eagle's nest on which two camera traps can been seen. Photo of personal collection.

2.3 Harpy eagle's circadian activity pattern

After retrieving the cameras, the photos were analysed on the presence of: A) a juvenile, B) an adult C) an adult with prey. Division between juveniles and adults has been made because different activity was expected. Adult with prey is chosen for the specific behaviour that may attract tourists. Using an Excel file, the results of each group specified for each nest and the time of the photo were documented. To describe the presence probability along the daily cycle, the circadian activity pattern was evaluated for the harpy eagle in general and for each group (A, B and C). To calculate the confidence interval for activity ranges, a bootstrap of 200 samples as recommended by Ridout & Linkie (2009) was performed. To perform a bootstrap, a sub-sample was taken from the dataset and the test was run again. The effect on the result was examined and thereafter the subsample was restored in the dataset. These steps were repeated 200 times. The 95% isoline represented the complete activity pattern and the 50% core kernel represented the activity core range. The program R 3.3.1 with the package Circular was used for the analyses and only independent records (>one hour apart) were considered.

3. Results

From July 2016 to January 2019, nine nests were monitored with camera traps. An average of 109 days of monitoring per nest (min: 3, max:356) resulted in 2827 independent records. This included 1618 photos of juveniles, 98 of adults and 90 of adults with prey, representing 18 adults and 9 fledged young.

Figure 3 shows the nest visit pattern of harpy eagles in general. The 95% isoline (representing the complete activity pattern) is lower during the night and highest during the hours of daylight, with a peak around 9 AM. The 50% core kernel (representing the activity core range) is between 8 AM and 5 PM.

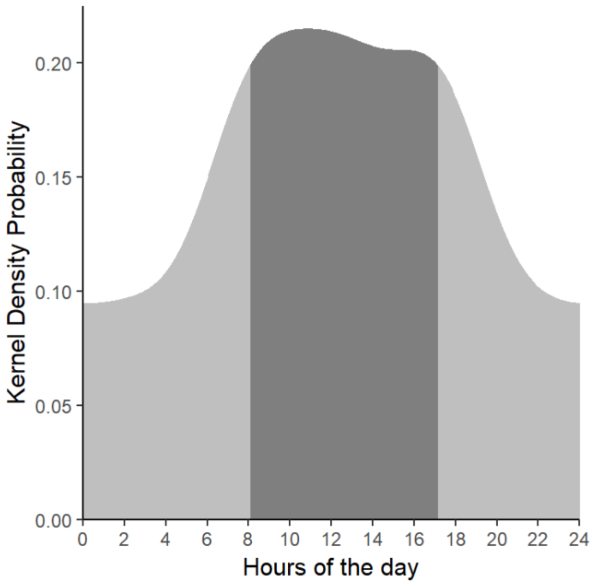

Figure 2. The nest visit patterns of harpy eagles in general. The solid line is the 95% isoline and indicates the total range of activity. The grey area is the 50% activity core range. N= 2827

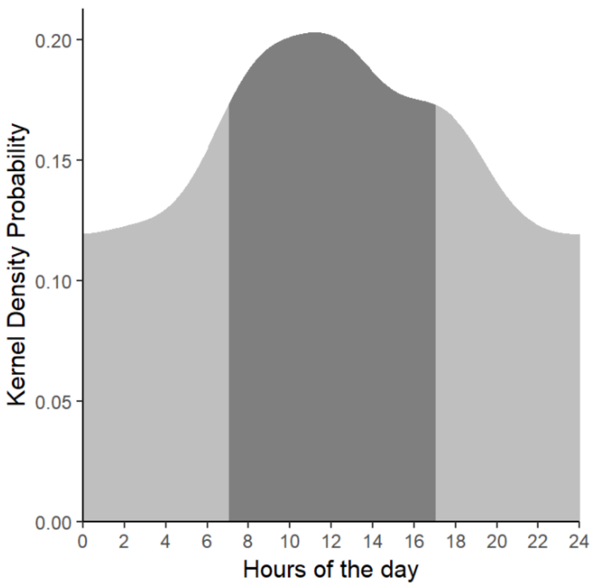

Figure 3. The nest visit *patterns of harpy eagle juveniles (group A). The solid line is the 95% isoline and indicates the total range of activity. The grey area is the 50% activity core range. N=* 1618

Figure 4 shows the nest visit pattern of the harpy eagle juveniles. The 95% isoline (representing the complete activity pattern) is lower during the night and highest during the hours of daylight with a peak around 11 AM. The 50% core kernel (representing the activity core range) is between 7 AM and 5 PM.

Figure 5 shows the nest visit pattern of harpy eagle adults. The 95% isoline (representing the complete activity pattern) is very low during the night and highest during the hours of daylight where there are two activity peaks. The first peak is between 8 and 11 AM and the second between 2 and 5 PM. The the 50% core kernel (representing the activity core range) is between 1 and 5 PM.

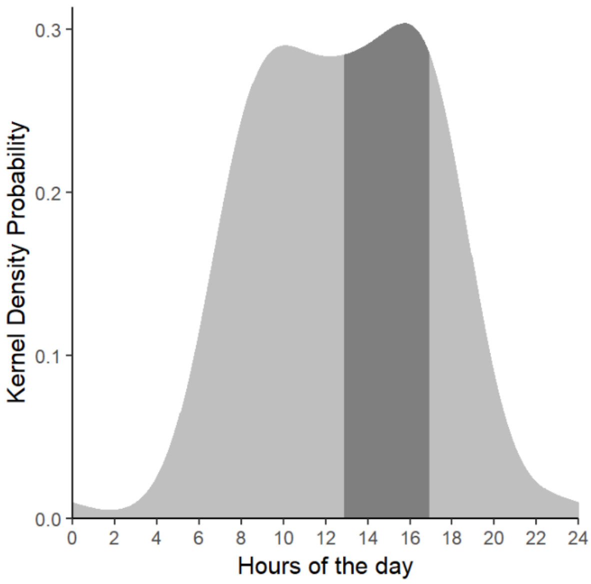

Figure 4. The nest visit patterns of harpy eagle adults (group B). The solid line is the 95% isoline and indicates the total range of activity. The grey area is the 50% activity core range. N= 98

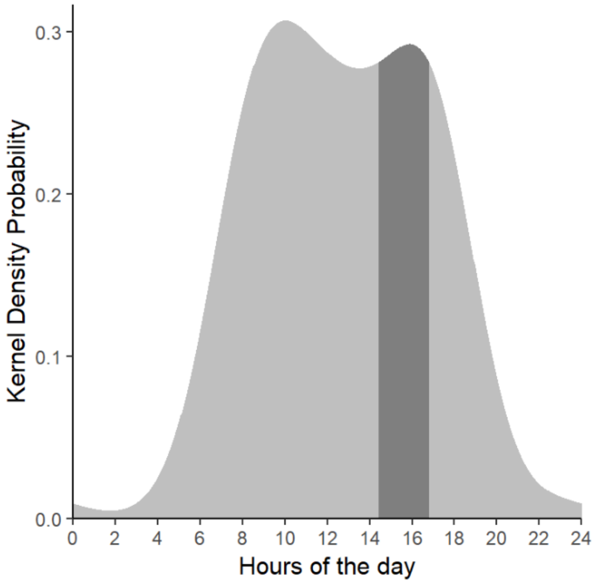

Figure 5. The nest visit patterns of harpy eagle adults delivering prey (group C). The solid line is the 95% isoline and indicates the total range of activity. The grey area is the 50% activity core range. N= 90

Figure 6 shows the nest visit pattern of harpy eagle adults delivering prey. The 95% isoline (representing the complete activity pattern) is very low during the night and highest during the hours of daylight where there are two activity peaks. The first and highest peak is between 8 and 11 AM and the second between 3 and 5 PM, the latter is also the 50% core kernel (representing the activity core range).

4. Discussion

This study provides a first indication of the activity hours of the harpy eagle at its nest. By predicting the best time window to see the harpy eagle at its nest, we may unravel this raptor to birders, wildlife photographers and other wildlife-enjoying tourists. While tourism on the harpy eagle may grow, this can be combined with tourism focussing on other species hosted in the great biodiversity of the Amazon (WWF, 2017).

Wildlife tourism is an important tool conserving the environment and sustaining local people. This is especially important in areas with high biodiversity and where local people depend on natural resources. While wildlife tourism employs local people, it also provides a career from wildlife tourism instead of logging and farming (Lowman, 2009). This in turn will help predators to be understood and accepted by local habitants.

Wildlife tourism is promising but can also have downsides. The risk-disturbance hypotheses states that organisms respond to human disturbance in the same way they respond to predation. Due to this response, animals become more alert, reduce their reproductive behaviour and may even shift territories (Frid & Dill, 2002). Harpy eagles build their nests in the tallest trees of the rainforest at heights of 27 to 43 meter. At our study site they were mainly Brazil nut trees. This makes it unavoidable to build viewing towers or tree platforms for the benefit of the tourists. While more harpy eagle nests become managed for wildlife tourism, it is important to examine the effect wildlife tourism activities (like human presence on the viewing towers) have, on the natural behaviour of the harpy eagle. This way adjustments can be made to avoid the possible negative effects or keep them as low as possible.

This study was conducted at 9 nests and at two of the nests the camera had failed or was broken by a harpy eagle. This resulted in decreased recording time of those nests. Despite these limitations. This study shows that harpy eagles as more active during the day which is confirming the literature stating harpy eagles as diurnal raptors (Bildstein, 2006). The main activity of the juveniles was found between 7 AM and 5 PM, the main activity of the adults between 1 and 5 PM and the main activity of adults delivering prey between 3 and 5 PM.

In conclusion, the best time to visit harpy eagle nests is between 3 and 5 PM. This time window holds several advantages for the activities concerning harpy eagle tourism. It would not only give the highest chance on seeing the harpy eagle but also on witnessing specific behaviour like parental care of feeding. Furthermore, controlling the visits in regard of nesting cycle and over multiple nests, allows tourism to be tailored for minimal impact on the harpy eagles. Current research is underway to compare the activity of harpy eagles between nests with and without tourism, to analyse if the visits from tourists can cause stress. As other apex predators, harpy eagles make good candidates as flagship for amazon conservation. Moreover, it is likely that harpy eagles may act like precursor to other forms of nature-related tourism in the Amazone. Questions remain over the biological reasons that triggers the peaks in activity and how would that vary in other areas of the amazon and beyond.

5. References

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6. Appendix: Bushnell Trophy Cam Aggressor

In this appendix, you can find all the specifications of the camera used during this research, the Bushnell Throphy Cam Aggressor.

Tabel 1. Specifications of the Bushnell Throphy Cam Aggressor.

Camera colour	Camouflage print
Dimensions (H x W x D)	16 x 11.4 x 6.4
Photo	Yes
Photo resolution	2, 8, of 24 MP (3MP sensor)
Video	Yes
Video resolution	1080p FULL HD (1920x1080)
Video length	Configurable between 5 and 60 seconds
Dynamic / smart-IR video	Yes
Hybrid functionality	Yes
MMS / Email functionality	No
Flash type	Visible Infrared Flash
Flash range	30 meter
Motion sensor range	30 meter
Field of view	45 degrees
Picture trigger time	0.15 sec.
Video trigger time	0.73 sec.
Trigger recovery time (picture)	0.75 sec.
Trigger recovery time (video)	1.5 sec.
Pictures per trigger (min-max)	1-3
Trigger interval	Configurable between 1 sec. and 60 min.
Colour footage during the day	Yes
Colour footage at night	No
Time lapse	Yes
Time lapse picture interval	1 picture every 1, 5, 15, 30 or 60 min. or 1 video every 5, 15, 30, of 60 min.
Built-in viewer	Yes
Display size	2.4 inch kleurenviewer
Details on each image	Date, time, temp, moon phase, configurable user label
Battery type	AA-batteries (NiMH rechargeable, Lithium, or Alkaline)
Number of batteries	8
External power plug	Yes
Memory	SDHC up to 32 GB
Included software	No software included
Password protection	No
Python lock tunnel/brackets	Yes
Other specifications	Configurable duty times (24-hours mode, day mode, and night mode), configurable sensitivity of the motion detector, configurable flash intensity, configurable shutter time at night.

Projeto “Construindo uma estratégia para a conservação da harpia na Amazônia” busca um candidato aos exames seletivos para o programa de Doutorado em Ecologia e Conservação da Biodiversidade na UFMT

Ao longo dos últimos anos temos associado pesquisa e conservação para proteger essa espécie na Amazônia mato-grossense. Assim, recentemente atingimos 20 ninhos que hoje são monitorados e protegidos pelo programa. Com o número crescente de ninhos encontrados, ficou claro que vamos precisar de novos colaboradores.

Estamos procurando uma pessoa interessada em cursar o doutorado trabalhando com as harpias da parte sul do estado de Mato Grosso, particularmente na região de tensão entre o Cerrado, Amazônia e Pantanal. São pré-requisitos saber lidar bem com pessoas de diferentes culturas, possuir bom inglês e não ter medo de estatística nem de altura.

Interessados podem marcar um papo com Everton Miranda:

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e-mail: mirandaebp@gmail.com

INSCRIÇÕES ATÉ 6 DE FEVEREIRO!

Inscrições para o doutorado estão abertas até 6 de fevereiro, e a seleção para o doutorado ocorre a partir do dia 14 de fevereiro. O aprovado pode contar com a nossa infraestrutura e financiamento, assim como com a base de dados já coletada até agora pelo projeto.

Orientador: João Batista de Pinho, Edital: http://www.ufmt.br/ufmt/site/userfiles/editais

Imagem de fundo da Amazônia por Neil Palmer

Species distribution modeling reveals habitat strongholds and reintroduction areas for the world's largest eagle

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Abstract

The highly interactive nature of predator-prey relationship is essential for ecosystem conservation, but predators have been extirpated worldwide from many ecosystems. Reintroductions comprise a management technique to reverse this trend. Species Distribution Models (SDM) are preemptive tools for release-site selection and can define levels of habitat quality over the species distribution. The Atlantic Forest of South America has lost most of its apex predators, and Harpy Eagles *Harpia harpyja* – Earth's largest eagle – are now limited to few forest pockets in this domain. Harpy Eagles are presumably widespread in Amazonian forests but habitat loss and degradation are advancing rapidly even in remaining wilderness areas. We aim to assess the suitability of remaining Atlantic Forest sites for Harpy Eagle reintroductions. We also aim to describe the suitability of threatened Amazonian landscapes for this eagle. Here we show that the Serra do Mar protected areas in southeastern Brazil is the most promising region for Harpy Eagle reintroductions in the Atlantic Forest. We also show that considerable eagle habitat has already been lost in Amazonia due to the expansion of the "Arc of Deforestation", and that Amazonian forests at present represent 93% of the species' current distribution. Once reintroduced, Harpy Eagles could reestablish top-down control over primates, sloths and other prey species that are currently damaging vegetation. Reintroduction and captive breeding programs have been undertaken for Harpy Eagles, building the technical and biological basis for a successful restoration framework. Our distribution range for this species represents a 41% reduction of what is currently proposed by IUCN. Furthermore, habitat loss in Amazonia, combined with industrial logging and hunting indicate that the conservation status of this species should be reassessed. We suggest researchers and conservation practitioners can use this study to expand efforts to conserve Harpy Eagles and their natural habitats.

Keywords: Arc of Deforestation; Atlantic Forest; *Cebus*; *Euterpe edulis*; top predator; reintroduction; *Sapajus*; trophic rewilding; trophic cascades.

Introduction

Extensive losses of apex predators is a pervasive conservation problem in ecosystems around the world [1]. Since the appearance of hominids ~2 million years ago, competition for wild prey, fear of direct attack on humans, and predation on domestic animals has led to the decimation of predator populations [2–4]. The subsequent cascading effects of predator-free populations of herbivores on plant communities can thus damage both natural vegetation and associated biodiversity [5–7]. These issues have placed large carnivores near the top of the conservation biology agenda [8,9], and reintroductions have emerged as one of the main tools to reverse these trends [10,11].

Few living predators are as quintessential creatures of legend as the Harpy Eagle (Fig 1, *Harpia harpyja*; [12,13]). Averaging 6.6 kg, the Harpy Eagle is the largest extant raptor on Earth, and is surpassed in size by only the extinct, island-living Haast Eagle (*Harpagornis moorei*; [14]), which humans wiped out from New Zealand's South Island. The Harpy Eagle is a forest species with the lowest reproductive rate of any living bird, producing a single young every 30-36 months [15,16]. Harpies have been persecuted over their entire range [17–20], and their feathers and talons are ubiquitous ornaments, with feathers often part of Amerindian arrows and headdresses [21,22]. Live eagles are also captured and kept by Amerindians as sources of feathers ([21]; personal observation). These factors, combined with habitat loss and degradation through logging, have already led to the rarity or extirpation of Harpies in much of their geographic distribution [23], especially in the Brazilian Atlantic Forest biodiversity hotspot [24].

Fig 1. Harpy Eagle *Harpia harpyja* adult female perched in the Atlantic Forest of Sooretama Reserve, state of Espirito Santo, Brazil [25].

The Atlantic Forest has suffered widespread losses of top predators [26]. Jaguars *Panthera onca* survive in the Atlantic Forest in only eight forest pockets, with a total estimated remaining population of only 300 individuals [27]. Relict populations of Harpy Eagles in the Atlantic Forest are currently known from around 10 breeding pairs and a few scattered individuals [28–31]. Harpy Eagles have been shown to exert strong behavioral and demographic control over their prey species [6,32]. In the absence of Harpies, prey populations often experience unfettered growth [33]. Consequently, they can be described as a keystone predator. Cascading consequences rising from the absence of Harpy Eagles are known to affect prey species. For instance, hyper-abundant populations of Black Capuchin Monkeys (*Sapajus nigritus*) cause high mortality of an arborescent palm (*Euterpe edulis*) of the Atlantic Forest because they rip out and eat the apical meristem, known as "palmito" [34,35]. This palm species is itself a threatened key species of the Atlantic Forest, and benefits many frugivore species by producing year-round infructescences, which are particularly important during the annual period of general, community-wide fruit scarcity [36]. Throughout the entire distribution of the Harpy Eagle, various species of capuchins represent the second most common primate prey [37]. Restoring Harpy Eagle populations would restore balanced communities in the ecosystem by reducing capuchin monkey densities, thereby preventing detrimental plant-herbivore interactions. Management guidelines could therefore benefit considerably from prioritizing which forest regions are most suitable for restoration of Harpy Eagle populations. Species Distribution Modeling (SDM; *sensu* [38]) can help obtain those answers.

Harpy Eagles are currently considered Near Threatened by the International Union for Conservation of Nature, IUCN [39]. While the species has vanished throughout much of its historical distribution [23], its widespread occurrence in vast tracts of Amazonian forests prevents Harpies from being listed in a higher threat category [39]. Meanwhile, questions remain about the quality of the supposedly homogeneously-pristine tracts of eagle habitat across Amazonia. Improving knowledge on this topic has high conservation value, since the ever-expanding cattle ranching frontier in a region of the southern Amazon known as the "Arc of Deforestation" has rapidly converted vast tracts of Amazonian forests into pasture and soy monoculture [40]. This forest destruction has led to loss of genetic diversity in Harpy Eagles [41]. SDMs could provide an improved basis for discussions about Harpy Eagle distribution in neotropical forests as well as in fringe forest habitats such as the Brazilian Cerrado and Pantanal wetlands, thereby helping to delineate the biogeographic boundaries of future reintroduction programs. Therefore, building SDMs for Harpy Eagles is central to a sound neotropical forest conservation strategy that could have collateral benefits for several other species.

A significant challenge in building a Harpy Eagle SDM is that to produce a robust result, one requires a significant amount of widely distributed geographic records [42]. Existing records, however, might be either too few or too patchy to produce a reliable SDM for such an elusive species. Finding Harpy Eagle nests has proven so difficult that the discovery of a single nest often sparks widespread excitement among ornithologists [43–45]. Furthermore, the few museum records of this species are severely restricted in range [46]. Finally, most museum skins include no data on the breeding status of the specimens, information that can greatly improve the quality of SDMs. We further highlight the unmet potential of the only attempt to compile a sufficient number of geographic records to document the pan-Neotropical Harpy Eagle distribution [23]; but this study failed to produce even the simplest map. Although two different, long-term Harpy Eagle field projects have each located more than a hundred nests, they have failed to compile and publish more than a small fraction of these valuable data. Meanwhile, many amateur birders have managed to painstakingly obtain numerous records of Harpy Eagles, many of which are available from online databases. Such databases have become extensive and provide considerable, often underutilized, information. Could a combination of citizen science and published scientific data therefore result in a major advance in an SDM for Harpy Eagles?

Here, we investigate two related topics in Harpy Eagle ecology and conservation: (1) we develop models to identify suitable reintroduction sites in the Atlantic Forest by generating and testing SDMs using environmental variables that are directly linked to Harpy Eagle ecology; and (2) we use these SDMs throughout the species range to identify strongholds and ecologically-suitable areas, which can help produce better conservation policies. SDM maps can help identify new field sites for future surveys, help create new protected areas specifically designed to conserve Harpy Eagles and identify marginal or suboptimal habitats as well as potential reintroduction sites. All these results can help improve conservation policies for the world's largest aerial predator.

Methods

Data collection

We compiled occurrence records using two main methods: standardized literature searches from Google Scholar and ornithological records at WikiAves (www.wikiaves.com.br). At Google Scholar, we used scientific and vernacular names of the species (in Portuguese, English and Spanish) to look for papers that may contain geographic data. We relied on geographic coordinates provided by authors, but only maps were often available, because some researchers believe that nest sites should remain undisclosed to avoid loss of chicks to wildlife traffickers. When we were unable to contact the authors, we extracted coordinates directly from the maps, but for records that included maps that were not sufficiently precise, we excluded those records. The WikiAves data retrieval was done up to 2016, with records spanning any date. To determine the location of a documentary photo or sound recording, we used municipal county (*município*) information from WikiAves in addition to the locality description, consulting the author whenever necessary. Data were double-checked for pseudo-replicates, meaning that we use only one confirmed record for specific nests or individual eagles that had been photographed by multiple birders. We also systematically searched the following georeferenced sound and photo databases: www.birdforum.net, www.xeno-canto.org, and www.macaulaylibrary.org. All records and their geographic coordinates can be found in **Supporting Information S1 Table 1**.

Breeders

Harpy Eagles are selective in their nest tree choice and almost exclusively nest in giant "T-shaped" bifurcations of emergent trees providing a stable platform [47,48]. As those trees used for breeding are of direct interest to the timber industry and are now absent from vast tracts of Amazonian logged forest [49], we distinguished records of breeding and non-breeding individuals as animals in logged landscapes may not be able to reproduce given the absence of appropriate emergent trees. We concluded that there was evidence of breeding if any of the following conditions were met: (1) eagles with greyish-white plumage, as such eagles are fledglings that are known to be unable to traverse flight distances longer than 2-km from their natal tree [15,16]; (2) adult individuals with brown breast coloration, which can only result from weeks of contact with tannin-rich leaves of the fresh nest material branches during incubation, and then brooding of the young chick [50]; and (3) any individual recorded at a nest. Consequently, we were able to identify locations that were in fact Harpy Eagle breeding sites.

Databases

For our SDMs, we used remotely sensed large-scale metrics as environmental variables. Specifically, we used data on bioclimatic variables and elevation [51], human population density (CIESIN, 2016), enhanced vegetation index, which is a measure of the amount of vegetation cover (NASA LP DAAC, 2016), canopy cover (NASA LP DAAC, 2016), and canopy height [54]. All environmental variables had a 1-km^2 resolution, and analyses were cut to fit our study area, namely the Americas south of 40°N latitude.

Species distribution modeling

To calculate the species distribution model, we followed three consecutive steps similar to the procedure of "random selection with environment profiling" [55]. First, we performed a rough classification of "suitable" and "unsuitable" habitat areas using an on-class support vector machine. To calculate this area, we set the condition that 90% of the observations must be within the suitable area, a procedure that has been shown to increase overall model discrimination [55]. Pseudo-absences were selected from the "unsuitable area", but this sample was not random. We were concerned that detection of Harpy Eagles may be positively correlated with human population density, because detection may be inflated in an area simply due to the presence of more human observers. To ensure that this bias did not affect model estimates, we selected pseudo-absences, giving weights for each cell, with weights proportional to the human population density of a given cell. In this manner, as the bias is present in both presences and pseudo-absences, it would not affect the model outcome [56]. We created as many pseudo-absences as our number of actual observations. Most of the models used here performed best when presented with an equal number of pseudo-absences and presences [57].

After pseudo-absences were sampled, we ran multiple environmental models: BIOCLIM, MAXENT, multivariate adaptive regression splines, logistic regression, generalized additive model, random forest, and support vector machine (SVM) networks, a machine learning approach. With this selection, we attempted to select most families of models, namely climatic envelopes, maximum entropy, splines, linear models, classification tools and SVMs. Since some of these models are sensitive to collinearity, we excluded bioclimatic variables that were correlated with one another. To do so, we ran a principal component analysis on the environmental values of our observations and pseudo-absences. We then scanned the variables in descending order of their eigenvalues. If a variable was not correlated by >0.7 with a previously-selected variable, it was retained in the model. With this procedure, we reduced our variable list to: seasonality of temperature (BIO4), annual precipitation (BIO12), precipitation in the coldest quarter of the year (BIO19), precipitation in the warmest quarter (BIO18), precipitation in the driest quarter (BIO17), mean temperature of the wettest quarter (BIO8), mean diurnal temperature range (BIO2), enhanced vegetation index, canopy cover, and canopy height. Using linear models, we added variables only as a main-effects model, as GAM models failed to converge if they contained interactions. In all models, we reserved 20% of our observations and pseudo-absences to test the models. We then used the model to predict the quality of each cell in the study area. The third step was to combine all of these prediction maps. We used a weighted average, whereby each map was weighted by its Area Under the Curve (AUC) values. Weighted average is indicated as a robust method for building model consensus [58].

We were further concerned that many of these observations did not relate to reproductive individuals, so we added a new step to the analysis. We performed again all three of the previous steps, but this time using only observations of Harpy Eagles clearly demonstrating that breeding was occurring. The results of this new analysis were then combined with all samples (including records of eagles that had been shown to be breeding and those of eagles that showed no sign of reproduction). We considered that for an area to adequately support sustainable Harpy Eagle populations, it must be close enough to a suitable reproduction area. To represent that, we drew a circle around each cell that showed suitability for reproduction, and the area of the circle was equivalent to the mean home range size of a typical Harpy Eagle pair. Using the same logic with a continuous metric of habitat quality for reproduction, we used a Gaussian blur on the reproductive predictions with a standard deviation of 25000/1.96 km. This value was chosen considering that a home range area equals 95% of an individual eagle's total range of movements [59], and that Harpy Eagle home range sizes are approximately 25 km^2 [60,61]. Merging different distribution models for different activities has been successfully used for California Condors (*Gymnogyps californianus*), showing robust predictive ability [62]. Once the final distribution was set, we used the criteria of equal sensitivity and specificity to categorize habitat quality as either "presence" or "absence". This threshold was superior to other 12 thresholding methods [63].

Results

We obtained records of Harpy Eagles with geographic references for all 19 countries that encompass their historical distribution. These include a total of 322 occurrences, 174 records of which consist of individuals that provide no clear evidence of breeding, while 148 records showed evidence of breeding. The largest number of records came from WikiAves (121), followed by scientific articles (118), unpublished theses and dissertations (49), governmental reports (17), birdforum.com (13), and four records from miscellaneous sources. According to the AUC values, all models yielded higher predictive power than random models (AUC range for non-reproductive models: 0.7553 (BIOCLIM) to

0.8867 (SVMs); AUC range for reproductive models: 0.7731 (BIOCLIM) to 0.8849 (SVMs, Table 1)). The distribution of those records and the overall potential geographic distribution of Harpy Eagles can be seen in Fig. 2.

Table 1. Area under the curve of several isolated models, the consensus between them, and the final model, where "All" refers to all records and "Reproductive" refers to records with credible evidence of breeding.

Model	Data	Isolated models	Consensus	Final
BIOCLIM	All	0.7547		
GLM	All	0.8224		
GAM	All	0.8429		
MARS	All	0.8099	0.7788	
RF	All	0.7698		
MAXENT	All	0.8381		
SVM	All	0.8416		0.8414
BIOCLIM	Reproductive	0.7189		
GLM	Reproductive	0.8549		
GAM	Reproductive	0.7163		
MARS	Reproductive	0.8846	0.8026	
RF	Reproductive	0.8657		
MAXENT	Reproductive	0.8491		
SVM	Reproductive	0.9029		

Fig 2. Spatial distribution of the 322 breeding (black circles) and non-breeding (white circles) records of Harpy Eagles in Central and South America. Forest cover is shown as a green scale gradient from white (non forest) to dark green (tall canopy forest). Lines represent country boundaries, and in the case of Brazil, state boundaries. Purple stars are potential reintroduction sites (i.e. habitat areas predicted to be suitable but currently lacking Harpy Eagle populations).

The predicted distribution of Harpy Eagles throughout the Neotropics is shown in Fig. 3. The model suggests that the Amazon forest is still the largest stronghold for the species, with a continuous area comprising 93.08% of all currently available habitat (Fig 4). The northern *cerrado* scrubland to wooded savanna macromosaic, mainly located in Brazil's state of Tocantins, has an extensive patch of intermediate quality Harpy Eagle habitat. Important habitat pockets remain in Mesoamerica, including southeastern Panamá near the Isthmus of Darien, the mosaic of protected areas that straddle Nicaragua and Honduras, and the Selva Maya protected areas that stretch across southern Mexico, Belize and Guatemala.

Fig 3. Prediction of the current geographic distribution of conditions fitting the ecological requirements of Harpy Eagles in Central and South America under contemporary forest cover. Records of breeding (solid circles) and non-breeding (white circles) eagles are also shown. Areas considered to be suitable habitat at present are shown in dark green, and uninhabitable areas are shown in red. Purple stars represent suitable reintroduction sites (i.e. habitat areas predicted to be suitable but currently lacking Harpy Eagle populations). Lines represent country boundaries, and in the case of Brazil, state boundaries.

The hyperfragmented landscape of the Atlantic Forest biome retains few available remaining habitat pockets that could currently support viable Harpy Eagle populations. One of them, in the lowland coastal forests of Brazil's northern Atlantic Forest (in the states of Espírito Santo and southern Bahia) has yielded recent evidence of current populations, including breeding pairs. The other, the Misiones Province of northeastern Argentina, has evidence of breeding in the last decade and recent records of non-breeding individuals. Finally, a ~7,000 km^2 cluster of forest habitat patches in a large mosaic of coastal protected areas — between the Paranaguá Bay in the state of Paraná and along the Serra do Mar in São Paulo — potentially shows the best area for future reintroduction attempts across the Brazilian Atlantic Forest, yet for several decades, this region has yielded no confirmed records of Harpy Eagles.

Fig 4. Categorical prediction of the current geographic distribution of conditions fitting the ecological requirements of Harpy Eagles in Central and South America under contemporary forest cover (see Methods section for thresholds criteria). Black lines represent the limit between predicted presence and absence. Records of breeding (solid circles) and non-breeding eagles (white circles) are also shown. The areas considered to be suitable habitat at present are shown in dark green, and uninhabitable areas are shown in red. Purple stars represent suitable reintroduction sites (i.e. predicted suitable habitat areas at present lacking Harpy Eagle populations).

Discussion

Careful selection of sites for reintroductions is key to successful species conservation and restoration. Here we delineate for the first time the plausible, global-scale distribution of Earth's largest extant eagle, which is of prime management and conservation interest. Three relatively-small sections of the Atlantic Forest biome demonstrate good habitat suitability for Harpy Eagles, namely: (*i*) the lowlands of the northern Atlantic Forest in Brazil; (*ii*) the Misiones green corridor of Argentina, and (*iii*) the Serra do Mar region of southeastern Brazil. Indeed, the Serra do Mar region has no current records of Harpy Eagles but could host successful reintroduction programs, while other suitable Atlantic Forest sites have recent or current evidence of breeding populations. The Serra do Mar forest corridor could host reintroduced populations that could become viable in the long term, much like the case of the Harpy Eagle reintroductions into Mesoamerica [64]. In contrast, the Amazon basin currently holds extensive tracts of high-suitability forest habitat, mainly concentrated in Brazil, eastern Peru and northern Bolivia. Additional vast tracts of well-suited habitat lie in southeastern Colombia, the Sierra Imataca of eastern Venezuela, and in Guyana, Suriname and French Guyana. Ecuador shows two pockets of suitable habitat, both east and west of the Andes. Mid-elevation tropical Andean forests above 1000 a.s.l. apparently provide suboptimal habitat for Harpy Eagles. Finally, our proposed distribution of over ten million square kilometers (10,401,993 km^2) represents a 41% reduction of the neotropical distribution area of 17,600,000 km^2 that is currently proposed by IUCN [39].

Range models can be interpreted as related to environmental suitability for the target species, where higher index values suggest better habitat conditions [65][66]. The Harpy Eagle's best sections of remaining habitat in the Atlantic Forest biome primarily consist of high-stature, lowland forest. One of these sections is the region that harbors some of the last breeding pairs of the species in the Atlantic Forest, specifically in the forest reserves of Sooretama, Linhares, Serra Bonita, Descobrimento, and Pau Brasil [28,29,67]. Over the last five centuries, Atlantic Forest landscapes have become highly degraded by conversion into sugarcane, coffee, and cacao plantations, slash-and-burn agriculture, and timber extraction [68], followed by extensive cattle ranching and eucalyptus monocultures, the latter two of which tolerate the resulting nutrient-poor soils. Thus, the Atlantic Forest has been an epicenter of forest loss in South America, beginning several centuries prior to the consolidation of the "Arc of Deforestation" global scare in the southern, eastern and southeastern Amazon [69]. After centuries of various direct sources of forest depletion, the Atlantic Forest currently presents small – but still worthwhile – hotspots for Harpy Eagle conservation. A highly-biodiverse, shade-grown-cacao-based economy [70] can still host successful conservation programs in the northern Atlantic Forest [71], and that includes Harpy Eagles. At the other extreme of the land use spectrum, the strictly-protected reserve network in the Serra do Mar forest corridor could provide promising habitat for a "rewilding" reintroduction project that would rebuild long disrupted forest trophic cascades in the southern Atlantic Forest. We recommend that conservationists planning significant reintroduction efforts for Harpy Eagles and other apex predators consider the findings from our models. We also emphasize that the parks within the Serra do Mar Atlantic Forest region should be given highest priority for release sites if any rehabilitated individuals become available within the Atlantic Forest and immediate vicinities.

A key factor regarding site selection in the Serra do Mar Atlantic Forest, where we recommend reintroductions, is that a sizable portion of this region falls outside the distribution of sloths in the Atlantic Forest [72]. In the absence of sloths, Harpy Eagles may take a disproportionately high toll on other arboreal mammal prey species, such as capuchin monkeys. In the Serra do Mar, capuchins have densities as high as 32 individuals per km^2 [73], and these primates are known to seasonally decimate threatened arborescent palms [74]. Problems related to capuchins crop-raiding forest plantations have also been reported elsewhere in the southern Atlantic Forest [75], where reintroduced Harpy Eagles could regulate monkey populations [32,33]. In the southern Atlantic Forest, remarkable work to connect fragmented landscapes is being carried out for Jaguars [76], and this model could be replicated for Harpy Eagles. Cross-fertilization between research programs for both of these top predator species could provide highly positive synergistic outcomes. Reintroductions have become a central focus of attention in the Atlantic Forest conservation agenda [77,78]. Reintroductions of top predators must, however, take into consideration issues related to a number of threatened arboreal mammals of the Atlantic Forest. Blonde Capuchins (*Sapajus flavius*; [79]), Maned Sloths (*Bradypus torquatus*; [80]) and Bristle Porcupines (*Chaetomys subspinosus*; [81]) are just a few examples of endangered arboreal mammals that may be further imperilled by reintroduced aerial predators, as has been shown elsewhere [82]. Fortunately, none of those prey species are in the set of regional sites where we propose reintroducing Harpy Eagles.

In Brazil, at least two independent conservation breeders have successfully reproduced Harpy Eagles (Refúgio Biológico Bela Vista and CRAX Sociedade de Pesquisa do Manejo e da Reprodução da Fauna Silvestre). Each of these breeders hold over 20 adult individuals, and other private breeders have a smaller number of adults and young animals. Meanwhile, The Peregrine Fund has developed a huge amount of know-how on Harpy Eagle reintroductions during a directed restoration effort for the species in Mesoamerica [64,83–85]. In addition, the Brazilian Harpy Eagle Conservation Program successfully released several rehabilitated individuals [61]. Eliminating the causes of extirpation must be addressed before embarking on any reintroduction effort in the Atlantic Forest. Given that large remaining portions of the historically-overexploited Atlantic Forest are no longer losing additional forest, the main threat to reintroduced Harpies would be reprisal or prophylactic killings by local residents [20,64]. Harpy Eagles also present a unique opportunity for ecotourism development that has shown positive results for both predators and local economies when implemented in a controlled, responsible manner [86,87]. Therefore, given the current amount and high quality of expertise, we believe that if appropriate funding can be raised, a successful reintroduction effort can become feasible.

The Amazon has long been considered the Harpy Eagle's last stronghold [39,88], and 93% of the current Harpy Eagle range is indeed encompassed by the Pan-Amazonian region. When we attempt to examine the status of Harpy Eagles in what we presume to be its primary Amazonian stronghold, we can simplify the analysis by looking at three broad areas of concern: (A) food; (B) habitat, and (C) mortality.

(A) Regarding the question of an adequate prey base, bushmeat hunting and the resulting competition with humans is a minor issue. Harpy Eagles feed primarily on sloths [89], which in addition to being abundant [90,91], are of minor importance as game species [92]. The effects of secondary forest, hunted or highly degraded forests on the foraging ecology of Harpies remains an open question because to date few has been published on their diet in unhunted, primary forests [93]. Recent observations in Mato Grosso, Brazil, and Sierra Imataca, Venezuela, suggest that this mega-raptor fares well in mid to late successional forest landscapes as long as it is not hunted by local people. Therefore, competition with humans over wild prey is hardly a problem. The ability of these eagles to feed young with wild prey – chiefly sloths – even in otherwise-hunted landscapes [60,94,95], suggests that Harpies are able to coexist well with humans.

(B) Concerning habitat, the extensive section of degraded forest that we found in much of the southeastern Amazon poses two problems regarding the "last stronghold" assumption: (1) habitat loss by deforestation and (2) habitat degradation by logging and wildfires. The cattle ranching frontier along the Arc of Deforestation continues to advance [96,97], and has already destroyed 21% of all primary terra firme forests of Amazonia. This impact has already led to a reduction in the global population size and genetic diversity of Harpy Eagles in this region [41]. Brazil's recent economic and political crisis and the massive decline in funding directed towards prevention of deforestation, combined with widespread relaxation of environmental laws, has effectively resulted in an unprecedented renewed increase in forest loss [97]. Up to 19,000 km² of primary Amazon forest becomes highly-graded each year by mechanized timber extraction [98], removing low-density giant emergent trees that Harpy Eagles require for nesting. Felling of nest trees by loggers is also a direct source of mortality of eagle chicks [60,99]. The relentless advance of cattle pastures was responsible for another 7,900 km² of forest loss in 2018 alone, which is increasing since 2012 [100]. Population densities of Harpy Eagles have been estimated at only 3-6 nests per 100 km² [101], thereby reiterating the crucial need for megareserves in Amazonia [102].

(C) Eagle killings by humans is another serious issue in the Amazon [20]. Amerindian reserves cover approximately 27% of the Brazilian Amazon [103]. In these Amerindian reserves, Harpy Eagles are universally considered to be prized birds for headdresses and arrow fletching [13,22]. Whereas indigenous societies may have gradually acquired a dynamic equilibrium with the wildlife that remained following the Pleistocene extinctions [104], the acquisition of firearms by Amerindians places much greater powers of destruction in the hands of indigenous people throughout the Amazon [105]. Native Amazonians wielding firearms, combined with the high prices commanded by indigenous feather headdresses when sold illegally as handicrafts, has greatly increased the pressure on Harpy Eagle populations inside Indian Lands. Although we are clearly in favor of indigenous land rights, sustainable use of wildlife often fails within indigenous territories and extractive reserves [106–108]. The discussion about hunting of threatened species cannot be trivialized or swept under the rug using the clichéd term "traditional practice". Rather, sensible rules and bag-limits, if any offtake can be defined as sustainable, as well as effective law enforcement are required to prevent endangered wildlife from melting away through careless use by communities who are directly connected to outside markets. Furthermore, when government land reform agencies settle millions of poor socio-economic migrants in primary Amazonian forest [109], the settlers tend to shoot in rapid succession every Harpy Eagle as well as other large, diurnal raptors [17,18,110].

The Harpy Eagle's "last stronghold" is therefore far from an adequate safety net, as Harpies are essentially running the gauntlet, as they are caught in the crossfire generated by market-integrated indigenous groups, high-grading loggers, land reform settlers, and cattle ranchers. This "witch's brew" of Amazonian threats should therefore be enough to convince IUCN and national agencies to reassess the conservation status of the Harpy Eagle.

The occasional occurrence of Harpy Eagles in some marginal habitats has been the subject of some discussion [44,45,111]. While early naturalists recorded this species in the Cerrado of central Brazil [88], Harpies were apparently never abundant in this ecosystem. The eagle's strong preference for giant, T-shaped emergent trees for nesting [47,48], and their specialized feeding habits concentrated on sloths (which are absent outside tropical forests) should render the Cerrado a marginal habitat for this species. Perhaps as a result of this, many maps show an erroneously disjunct distribution for the species with two separated pockets in South America. Our results suggest that a pocket of acceptable Harpy Eagle habitat exists in the northern Cerrado and in much of the transition zone between the Cerrado and the Amazon, which could explain occasional reports of individuals shot and nests found in such areas. In the Pantanal wetlands, our SDMs suggests that this species is expected to occur only in its northern parts (with very limited habitat quality and range), where the few direct records have been documented for the species [44]. An extensive search effort of the entire Pantanal wetlands for the similarly-huge nests of Jabiru storks (*Jabiru mycteria*) found no Harpy nests whatsoever, suggesting absence [112]. A couple of Harpy Eagles have been recently documented at the Calileuga National Park in the Yungas of northwestern Argentina, which contains a small habitat patch that our SDM shows to be of low quality. Another peripheral habitat area that shows several pockets of good suitability are the Caribbean Antilles. It is interesting to note that none of the bird-rich fossil records of Antillean islands have uncovered any remains of Harpy Eagles. Several species of giant raptors that humans drove to global extinction are known from this archipelago [113,114]. These extinct predators include a giant flightless owl (*Ornimegalonyx oteroi*), a giant flying owl (*Tyto pollens*) and a giant, buteo-type hawk (*Amplibuteo woodwardi*). It would be interesting to investigate if those extinct Antillean raptors performed a similar predation role on both terrestrial and arboreal sloths of the Antilles as Harpy Eagles exert on arboreal sloths in continental forest ecosystems. These musings open many interesting lines of inquiry regarding convergent predator-prey relationships in Caribbean islands and continental Neotropical forests.

In conclusion, we show that the most suitable sites for Harpy Eagle reintroductions in the Atlantic Forest are located in the Serra do Mar forest corridor. In the currently hyper-fragmented landscapes of the Atlantic Forest, this habitat corridor represents the largest tropical forest continuum available in the Atlantic Forest that could host a healthy population of Harpy Eagles. Much of this forest corridor lies within protected areas that could support a reintroduction project for Harpy Eagles, so environmental authorities should prioritize this corridor as a release site for Harpies. In the Amazon – the Harpy Eagle's last stronghold – much of the forest that could be considered prime habitat for the species may in fact already be badly degraded by the rapidly-expanding Arc of Deforestation and associated logging frontiers. Here we sound the alarm that the supposedly uniformly high-quality of Amazonian forests as a long-term refuge for Harpy Eagles is far from ideal. Rather, a perverse mix of anthropogenic threats has been driving Harpy Eagles to many local extinctions long before the forest cover is completely removed. We therefore suggest that in light of these findings, the IUCN status of this keystone predator should be urgently reassessed.

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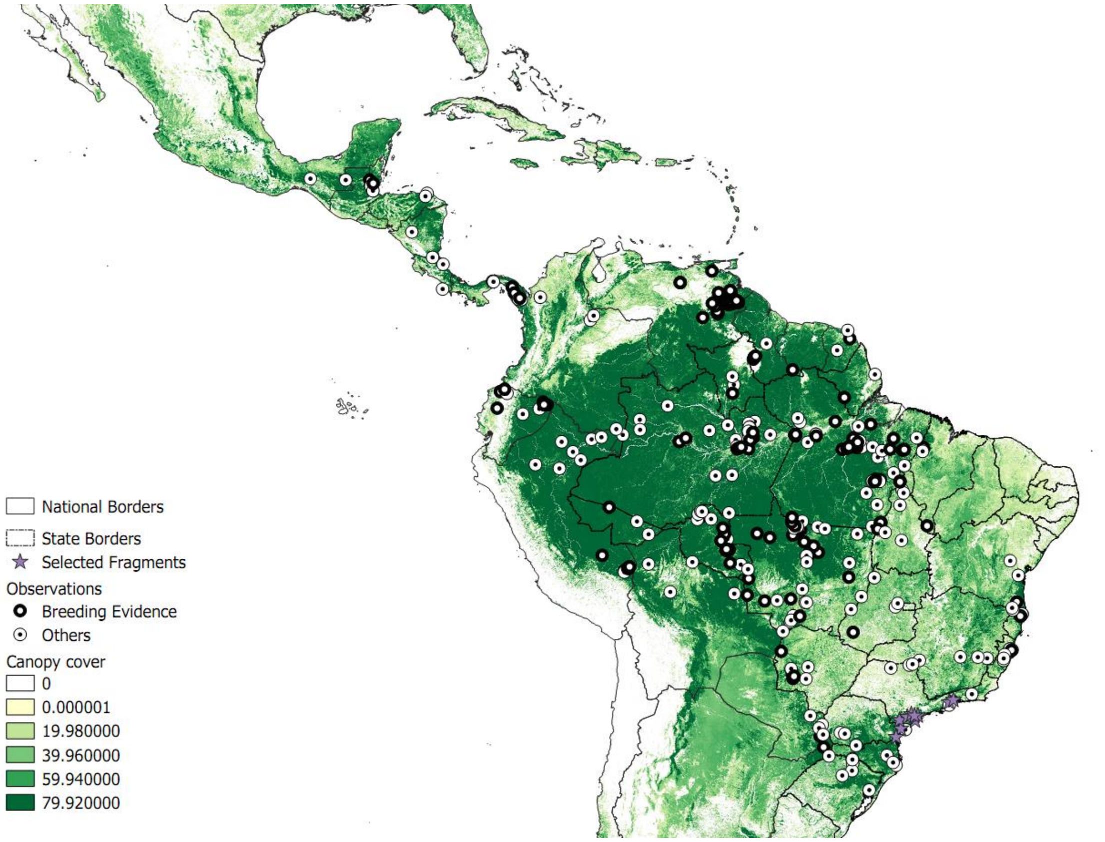
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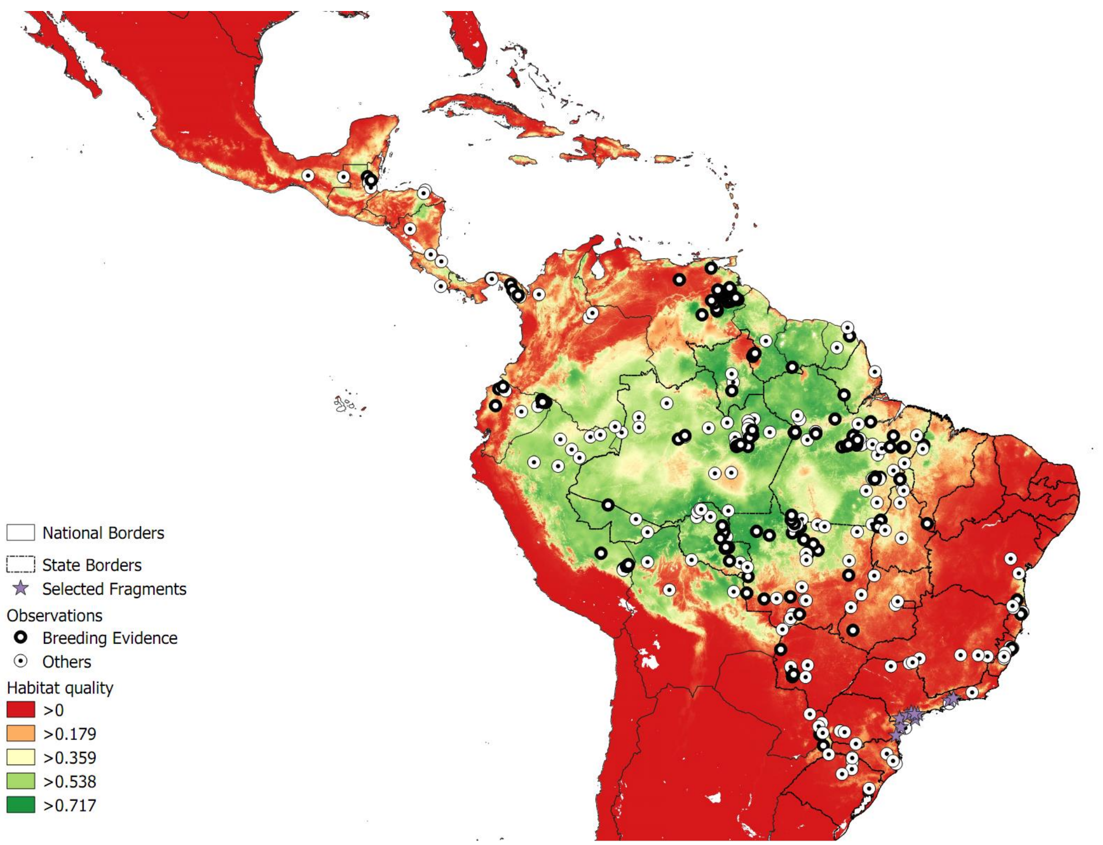
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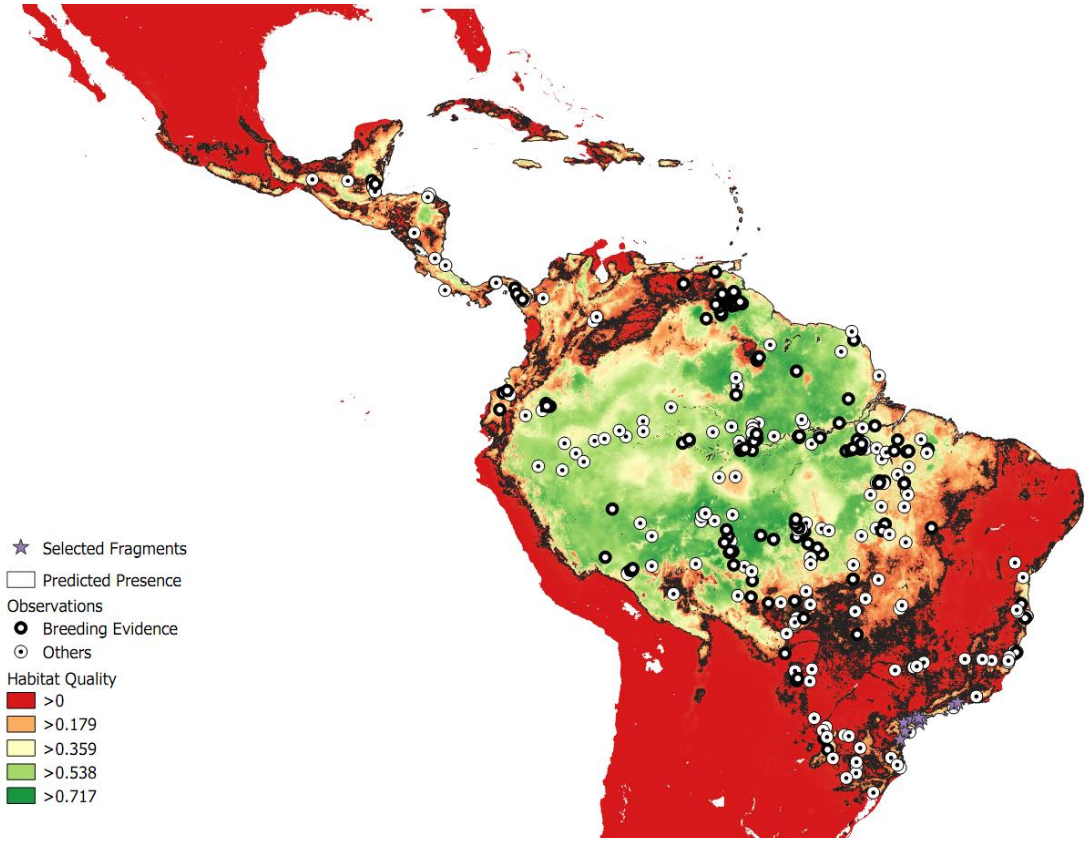
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