Deforestation, fires, and lack of governance are displacing thousands of jaguars in Brazilian Amazon

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Abstract
The rate of deforestation and the number of large wildfires are increasing in the Amazon. Illegal loggers, miners, ranchers, and farmers all have contributed to this increase. Their activities have dramatic consequences for biodiversity, ecological services, and people. In this study, we estimated the number of jaguars affected by deforestation. We focused on the Brazilian Amazon from August 2016 to December 2019. Further, we analyzed the effects of socio-geographic determinants of deforestation and state policies. To do so, we used deforestation data from DETER-B satellite system. The number of jaguars within each deforested area was pulled from a previous study, which provided jaguar abundances for jaguar entire range. We assumed all jaguars within a deforested area were affected (displaced or killed). To determine the underlying causes of jaguar loss, we regressed the number of jaguars lost per state and year against the proportion of total forest area within reserves, distance to forest border, and monetary efficiency in cattle production. We estimate a total of 1,422 jaguars have been displaced/killed in recent years (2016: 488, 2017: 360, 2018: 268, 2019: 354). Only the proportion of protected area had an effect in reducing jaguar deforestation. We discuss how our work could result in near real-time monitoring of jaguar displacement and how policies such as wood certification, more efficient cattle production, and centralizing governance may be solutions.

KEYWORDS
conservation, deforestation, DETER-B, fires, Panthera onca

1 | INTRODUCTION

In 2019, the Brazilian Amazon was highlighted on international media due to a series of coordinated arsons drawing focus to the destruction of the forest by illegal loggers, miners, ranchers, and farmers (Eisenhammer, 2019). This event was unprecedented in its coordination. Arsonists used social apps to synchronize their acts in a single day: the “day of fire” (Eisenhammer, 2019). This day represents a spike in deforestation in the Amazon forest in its most conspicuous form, forest fires. However, deforestation itself is not new. The deforestation rate is increasing...
despite their clear importance to multiple ecological services and their use as indicator of environmental integrity, jaguars are directly threatened by deforestation (romero-munoz, morato, tortato, & Kuenmerle, 2020). The issue is often compounded by deforestation often utilized as open space for cattle ranching and agriculture. jaguars often hunt cattle (Carvalho, Zarco-González, Monroy-Vilchis, & Morato, 2015), a behavior that triggers retaliation hunting by cattle ranchers (Marchini & Macdonald, 2012). Thus, both directly and indirectly, the survival of this species is dependent on the presence of forest in the Amazon region.

It is essential to understand how fires and changes in land use influence the jaguar population in Amazon region. To identify strategies for reducing negative human impacts on jaguar populations, we estimated the number of jaguars that occurred in deforested areas during the period 2016–2019. We assume those animals were either displaced or killed by this deforestation, although the exact fate is not known. Given that jaguar density is directly associated with forest cover (Jędrzejewski et al., 2018), we expected that jaguar displacement/killing would increase in 2019. We also analyzed this trend state by state and year by year, to obtain a more detailed picture of the process.

Likewise, it is important to understand how fires and deforestation influence jaguar displacement/killing. We were interested in three social and geographic variables: distance to the forest border, the proportion of protected forest, and cattle production efficiency. the first variable is due to an effect known as the Arch of Deforestation (Becker, 2005). Deforestation in the Amazon seems to progress from South to North. One of the reasons for that phenomena is likely logistic access. It is harder to access areas in the center of the Amazon than on its border. Thus, we would expect distance to any forest border to decrease deforestation and hence jaguar displacement/killing. The second variable was chosen based on the assumption that protected areas prevent deforestation. We expect states with most of their forest protected would have little to no deforestation and thus little jaguar displacement/killing. For the third variable we expected an increase in production efficiency in cattle farms (measured as yearly monetary profit over monetary costs) would decrease jaguar displacement/killing. A study on deforestation in Cameroon (Epule, Peng, Lepage, & Chen, 2014) suggests increasing farmland throughput could reduce the pressure on farms to utilize all land available, creating space for protected areas. This release of farmland to invest in reserves is also positive for farming overall, since it allows the farmers to have a provider of ecosystem services within their land, ensuring more indirect benefits such as pollination protection against
drought. A study on the cattle production efficiency in Amazon, suggests current farmlands could be considered inefficient, operating at 38% efficiency (Igliori, 2005). Lastly, we discussed different strategies to reduce the loss of jaguars, with an emphasis on strategies instituted at the landscape scale.

2 | METHODS

2.1 | Background data

To estimate how many jaguars have been killed or displaced by the deforestation between 2016–2019, we first need to assess which areas have been deforested. We used satellite data from DETER-B system of the Brazilian Institute for Space Research (Instituto Nacional de Pesquisas Espaciais [INPE], accessed on January 5th, 2020). This dataset includes deforestation throughout the Brazilian Amazon, from August 2016 to December 2019, and provided polygons representing deforested areas larger than 6.25 ha. This system uses satellite images from satellites Resourcesat-1, CBERS-4, and AWiFS, which allow deforestation updates every 5 days in the Amazon region, a “real-time” estimate of deforestation instead of previous yearly estimations (Diniz et al., 2015). These images are processed by a linear spectral mixture model to infer the fraction of soil, shade, and vegetation in the image. (Diniz et al., 2015). This percentage of exposed soil and appearance is then visually classified by INPE operators in eight classes: “clearcut deforestation,” “deforestation with vegetation,” “mining,” “moderate degradation,” “intense degradation,” “burnt scar,” “regular selective logging,” and “conventional (irregular) selective logging” (Diniz et al., 2015). Classes are distinguished based on color tonality, shape, texture, and context. More information on each class can be found in Diniz et al. (2015). This information is then audited to reduce human errors (Diniz et al., 2015). DETER-B had an 80% agreement in classification with INPE’s PRODES system (Diniz et al., 2015), whose accuracy reaches 90% (Pendrill & Persson, 2017). Using those parameters, we attempt to discern which classes of deforestation would lead to jaguar displacement and death.

For our analysis, we considered the classes “clearcut deforestation,” “deforestation with vegetation,” “mining,” “moderate degradation,” “intense degradation,” “burnt scar,” to be classes that would displace jaguars. These classes either expose the ground or show growth of secondary forest (“deforestation with vegetation”) (Diniz et al., 2015). Secondary growth is avoided by jaguars in comparison to tall forests, so we assumed that animals in those areas would be displaced the surrounding region (Conde et al., 2010). We excluded regions with selective logging (either regular or conventional) because it was found that these species still occur in areas with selective logging (Polisar et al., 2017). With this information, we settled for areas in which we believed we could not find jaguars.

Once we had the areas where jaguars were displaced/killed, we attempted to identify how many jaguars would be in these areas. For that, we based our estimation on a previous spatially explicit estimation of jaguar abundance (Jędrzejewski et al., 2018). In this estimation, authors collected density data from 117 camera trap studies conducted in pristine locations in South and Central America (7 in Argentina, 22 Belize, 13 Bolivia, 15 Brazil, 4 Colombia, 3 Costa Rica, 1 Ecuador, 7 Guatemala, 4 French Guiana, 3 Guiana, 17 Mexico, 2 Panama, 1 Paraguay, 6 Peru and 6 Venezuela), from 2002 to 2014 to generate a model of jaguar density (Jędrzejewski et al., 2018). For that, Jędrzejewski et al. (2018) used density data from the studies mentioned above to create a linear model, with density as the response variable and a series of environmental variables as explanatory variables (temperature, net primary productivity, etc.; see Jędrzejewski et al., 2018 for further methods).

However, Jędrzejewski et al. (2018) argue this data might not be representative of jaguar density in impacted regions, since density data reflect regions with pristine environments. To account for that, the authors also developed a species distribution model of jaguars, using further presence records throughout the Americas. This second model was also a generalized linear model, with probability of presence as the response variable, and the same environmental variables as explanatory variables. As a result, this second model could predict a probability of occurrence for each location given a set of environmental variables. This probability was interpreted as a measure of habitat quality, the higher the probability, the higher is the quality for the animal. This probability was then multiplied with the density predicted by the first model to generate a final density prediction for a given set of environmental variables.

After this model was constructed, it was necessary to spatialize these predictions. Jędrzejewski et al. (2018) divided the Americas into pixels of 1 km² and the values of environmental variables for each pixel were obtained from satellite images. Based on that, the density on each 1 km² pixel was calculated as explained above. This density was later multiplied by the area to obtain the estimated number of jaguars in each 1 km² pixel. As a result of this process, Jędrzejewski et al. (2018) produced a single map, ranging from Southern USA to the southern end of South America, covered in 1 km² grid cells, each with an estimated of the number of jaguars.
2.1.1 | Novel methods

The DETER-B and the Jędrzejewski et al. (2018)’s jaguar density map, however, are not immediately comparable. The DETER-B dataset has a resolution of 6.25 ha compared to 1 km² for the jaguar density data. Thus, we downscaled the DETER-B data by creating a grid of 1 km² cells and assigned to each cell the proportion of its area covered by one of DETER-B polygons. Following that, we multiplied that value by the estimate of abundance of jaguars in that pixel. This multiplication implies all jaguars in that area were affected. They were either displaced by human activities or killed; however, the precise fate is unknown. We only assume such a destructive event in the landscape will remove jaguars from the region. Once we had the total number of jaguars killed or displaced, we converted it to a percentage of the total number of jaguars in the state.

To infer the cause of these displacements and determine whether different states perform better than others, we calculated the number of deaths/displacements by year and by Brazilian state, using the same methods above. Further, we measured the relationship between displacement and socio-geographical variables. We calculated three variables: percentage of unprotected forest, distance to the Arch of Deforestation, and cattle efficiency.

We chose percentage of unprotected forest to measure the remaining forest available to be deforested. Throughout the year several states had their cover almost entirely extirpated. Therefore, it might be possible that the state has few jaguar displacements because most of its unprotected forests are gone. To measure that, we used satellite images of yearly vegetative cover from the MODIS terra satellite (MOD44B), from the period of 2016 to 2019 (Dimiceli et al., 2015). This data had resolution of 250 m, and we cropped the layers to consider only the studied states in Brazil. After that, we categorized the image in forest or non-forest, considering areas with more than 50% vegetation cover as forested. We then masked the image with polygons representing the protected areas, from the World Protected Regions Database (IUCN & UNEP, 2009). After masking the image, we were left with a binary map of values 1—(unprotected forest) or 0—(non-forest areas or protected forests). We aggregated the image by a factor of 400, with each new pixel representing the sum of forested pixels within it. Following that, we summed the values of pixels in each state to generate a state-wide estimate of unprotected forest pixels.

We also did a similar process to the original map of forest vs. non-forested areas (before the masking by protected areas). We aggregated it by a factor of 400 and summed it the values per state. That produced a state-wide estimate of total amount of forest pixels, which could be compared with the number of unprotected forest pixels described above.

We also measured distance to the border of deforestation, that is, distance to a point of entry in the forest, to represent that it is logistically harder to deforest in the center of a continuous piece of forest than at its border. To do so, we took the binary forest non-forest image from before, and inverted it, to generate an image of potential entry points. This image was clipped to exclude areas outside of the states. After that, we calculated the distance of every forested pixel to the closest non forested pixel. These distances, were aggregated by a scale of 400, using the mean value. Then, we calculated the mean value of each pixel within a state per year.

Lastly, we took the average efficiency of cattle production for each state from a previous study (Igliori, 2005). We used this metric following the hypothesis that more efficient cattle management is less land intensive, and thus highly efficient properties can afford to preserve the amount required by law without losing much profit. As a result, we expect more efficient cattle production to lead to lower jaguar displacement.

Once we had measures for each variable, we tested their effect using two linear models. The first considered information per state and year, having displacement as response variables, and state, year, proportion of covered forest outside of protected areas, and average distance to edge as independent variables. Meanwhile, we produced a second regression using data averaged across years. This regression measured displacement/killings per state against efficiency. All analyses were done in R v.3.6.2 (R Core Team, 2019), using packages sf and raster (Hijmans, 2020) for spatial analysis and car (Fox & Weisberg, 2019) for type sums of squares in the linear model.

3 | RESULTS

We estimate a total of 1,422 jaguars (1.8% of the population) have been displaced/killed in recent years (2016: 488, 2017: 360, 2018: 268, 2019: 354; Figure 1). As we expected, we found that in 2019, the trend of reduction since 2016 was reversed. On a state by state basis, Pará (n = 537) and Mato Grosso (n = 438) showed the highest number of displacements/killings across all years combined. Maranhão state (n = 134) showed a large reduction in displacement/killings across the years. The largest state in the region, Amazonas (n = 95) showed a small number of displaced/killed jaguars. Only two states show a decrease in the year 2019, Tocantins and Maranhão (Table 1). Regarding the socio-geographic variables, we
found support for an effect of forest cover ($\beta = -366.406 \pm 141.824$, $t = -2.584$, $p = .016$). We also found an effect of state ($F_{8,24} = 30.3815$, $p < .001$). In contrast, we found no support for an effect of distance to the border ($\beta = 0.008 \pm 0.006$, $t = 1.217$, $p = .235$) or year ($\beta = -5.365 \pm 2.665$, $t = -2.014$, $p = .055$). Using our second regression, we found no support for an effect of cattle efficiency ($F_{1,7} = 0.3501; p = .572$).

### DISCUSSION

We present a broad assessment of the dramatic effects that deforestation and fires can have on the largest cat in the Americas. A loss of 1,422 jaguars in just 5 years suggests that time is short to avert jaguar decline. This trend varies widely among states, with some showing the opposite trend of the entire country (e.g., Tocantins and Maranhão states). However, four states (Acre, Amazonas, Roraima, and Rondônia) showed a trend of increasing displacement/killing that was not triggered in 2019, but instead is a continuous process for many years. Thus,
although there is a clear increase on average in 2019, this effect is different among states, which suggest that policies at state levels are critical for conserving jaguars.

Some of this variation in jaguar loss from state to state is geographic. States that have less unprotected forests are less prone to jaguar displacement. This result can be interpreted two ways: First, the inverse relationship between proportion of protected forest and number of displaced jaguars indicates conservation units reduce jaguar displacement/killing, at least to some level. However, this effect is weak, explaining little of the variance in the displacement (Figure 2). Much more of the variance is captured by states across years, indicating that there are more determining factors than protection alone. Alternatively, the same result may stem from a bleaker interpretation. Since, to our knowledge, no new conservation units have been created in the studied years, the reason for states having large proportion of forest being protected is because they lose most of their unprotected forest. For example, Maranhão has 25% of its original cover. Of those 25%, 70% are in protected areas (Celentano et al., 2017). The effect of protected areas may be small overall, but for some states that is all they have left.

Some states are associated with the Arch of Deforestation, a region where the agricultural border advances towards the forest, going from the east and south of the Brazilian state of Pará towards the west, passing through the states of Mato Grosso, Rondônia, and Acre (Michalski, Peres, & Lake, 2008). It is easier to transport machinery and workforce to the border of the jungle than to its core. That makes it easier to start the deforestation process from the original borders of this biome. Although the effect of the Arch of Deforestation is visible, we found no support for an effect of distance to border in the displacement of jaguars. Perhaps, jaguars’ requirements would already push the species into deeper and more intact forests, reducing their abundance in places where human activity is prone to start. However, the mechanism still requires study to obtain more detailed explanation.

We were surprised to find that cattle efficiency did not have a perceivable effect on jaguar displacement, as initially hypothesized. Reduction in the use of land with increased efficiency has been a long-standing hypothesis in regards to conservation policy, also known as land sparing (Phalan, Onial, Balmford, & Green, 2011). Yet, we found no effect of efficiency on the displacement. Barretto, Berndes, Sparovek, and Wirsenius (2013) offer an explanation to this conundrum. Increasing efficiency often leads to greater consumption of input materials (e.g., larger grasslands, more roads, an increase in local industries to supply additives), which would also lead to greater use of the land. Land use is only reduced if land is already scarce, either due to high price of land or due to government enforcement (Barretto et al., 2013; Strassburg et al., 2012). If enforcement is already underway, some studies suggest methods that can be used to increase efficiency. Pasture rotation, along with planting...
legumes within the pastures, may increase livestock mass growth (Latawiec, Strassburg, Valentim, Ramos, & Alves-Pinto, 2014). At a larger scale, municipalities with larger populations tend to handle cattle more efficiently (Igliori, 2005). Paradoxically, higher education tends to decrease cattle efficiency as municipalities switch to other agricultural practices (Igliori, 2005). This suggests the bottleneck for the preservation of Brazilian Amazon is enforcement. Other activities may contribute to forest preservation once enforcement is present, but cannot replace it. Some of the changes in jaguar numbers during the years might result from policy changes. Policy, however, is hard to quantify. Currently, most states in Brazil lack a unified database of permits for deforestation, along with statistics of anti-deforestation measures. Thus, it is currently impossible to analyze the efficiency of current policies, or even to compare them across states. We can, however, suggest some policies that might be effective in fighting deforestation.

For example, Tocantins’ government implemented a policy of reducing the number of permits for deforestation in the years 2018–2019 (Caldas & Government of Tocantins, 2019). Maranhão has also registered record decline in deforestation, much larger than expected by its own action plan to reduce deforestation (State of Maranhão, 2011). This reduction has been attributed to technical support provided to local farmers by the state secretary of the environment (SEMA, 2019). However, the same may result from a lack of forest to cut down.

On a negative side, the states of Pará and Mato Grosso lead in the number of jaguars displaced by deforestation. Cumulative deforestation in these states is clearly related to the expansion of soybean and cattle areas, partially for exportation to China (Fearnside & Figueiredo, 2015). The dynamic of land use changes in these states seems to be connected. Advances of soybeans into pastures and forests in Mato Grosso displace ranching activities into the forests of Pará (Arima, Richards, Walker, & Caldas, 2011). Moreover, recent state policies can also account for part of deforestation patterns. For example, Pará introduced an ecological tax on merchandise and services. While it has been capable of raising funds to direct to municipalities with high level of deforestation, there was no impact on deforestation rates (Tupiassu, de SL, & Gros-Désormeaux, 2019). A previous study analyzed the distribution of this money and found that many municipalities were not investing this extra tax in environmental projects (Tupiassu et al., 2019). There was also no requirement (only a suggestion) by the state that this money would be applied toward that end. Thus, the state had no means to divest or otherwise enforce this money would be dedicated to their conceived goal.

The state of Mato Grosso was the second state with the highest number of jaguars displaced by deforestation and fire \( (n = 438) \). In 2019, the state recorded the highest rate of deforestation in the last eleven years (Valdiones, Silgueiro, Cardoso, Bernasconi, & Thuault, 2019). Although the current scenario is unfavorable for habitat protection for jaguars in Mato Grosso, the state has already been previously recognized as an example of governance in reducing deforestation (DeFries, Herold, Verchot, Macedo, & Shimabukuro, 2013; Fearnside, 2003). This reduction in deforestation (in 2010) in Mato Grosso was the result of a combination of market forces, policies, enforcement, and improved monitoring (DeFries et al., 2013). One of the aspects was the increase in enforcement, possible through the communication between the national space institute and the local environmental agency, which automatically evaluation whether a farm had been illegally deforested. Mato Grosso has proven that it is possible to use the government’s capacity to impose regulations and influence deforestation trends (Fearnside, 2003), although it is unclear what changed after 2011. These measures should be stimulated to ensure the integrity of habitats for jaguars.

Another policy is to require certified sustainable timber in each state. There are current certification initiatives for wood trading that ensure sustainable production. However, these certifications are often not economically advantageous, since the Brazilian market is uninterested in paying higher market prices for certified products (Dasgupta & Burivalova, 2017). Further, wood loggers often engage in land grabbing, a process where land with uncertain governance is exploited without proper licensing. The ease of this process generates a tragedy of the commons scenario (Hardin, 1968), where the costs of clear cutting are shared by society (loss of forest land without clear ownership) and benefits go to a small group (clear cut profits, with no land expense). Thus, several studies suggest clear ownership of land would reduce the benefit for clear cutters (Reydon, Fernandes, & Telles, 2020; Stabile et al., 2020).

Although current federal policies are focused on decreasing enforcement, some of their directives might be used to improve conservation indirectly. The current Brazilian president was elected under a promise of reducing bureaucracy. Bureaucracy has been shown to enable deforestation when it is present in the form of shared competencies and governance. For example, in Cameroon, the division of the previously existing ministry of forestry in to a new ministry of forestry and another of environment generated overlapping competencies (Epule et al., 2014). Further, when actions required cooperation between both, communication speed was reduced by the extra formalism of inter-ministerial communication (Epule et al., 2014). Similar issues have been found across...
government sectors in multiple countries, often dubbed the “curse of common competencies” (Steytler, 2003). Brazil might face similar or perhaps higher levels of fragmentation of authority. Its system of environmental protection is divided in two levels. At the federal level, Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) is responsible for licensing private environmental projects. However, interested parties also have to pursue licensing with the local state environment agencies, which often have local environmental laws and independent mechanisms of enforcement. Previous studies recommend ameliorating these issues by centralizing authority in a single agency (Epule et al., 2014), which would be in alignment with the current drive to reduce bureaucracy.

The success or failure of these government measures is usually assessed based on deforestation rates. In this study, we present a new metric, based on the displacement/killing of a charismatic species and with a recognized role in the maintenance of Amazonian biodiversity. Despite showing a significant reduction in jaguar numbers, our estimation is likely conservative. Not only do we assume that all animals in a deforestation polygon are displaced/killed, but we have not considered displacement and killing for other reasons. For instance, as a secondary effect, deforestation increases the access to formerly remote areas facilitating poaching and retaliation hunting (Romero-Muñoz et al., 2020). These factors combined were responsible for the drastic jaguar population decline in the southern portion of the species distribution (e.g., Romero-Muñoz et al., 2018). A possible example is Iguazu National Park, while the species density was estimated to be 2.96 individuals/100 km² in 1995 (Crawshaw, 1995), about 10 years later the jaguar estimated density was 0.545 individuals/100 km² (Paviolo et al., 2008). Deforestation and fire rapidly transform source habitats for jaguars into sink habitats, with resource restriction and increased risk (Romero-Muñoz et al., 2018). With this, we can assume that the numbers presented here represent a starting value for estimating the subsequent impact of deforestation and fire on the jaguar population.

Given the circumstances that information on jaguars is scarce on the scale proposed by this study, we assume some caveats, such as not offering a measure of error associated with each pixel and considering the densities as constant over the period from 2015 to 2019, since Jędrzejewski et al. (2018) density estimates covered 2002–2014. However, we still believe the information presented here could not be gathered through other means, and a potential loss of 1.8% in the jaguar population deserves to be noted, even if only as a warning.

The approach and data presented here, despite some limitations, can be built on to further improve conservation strategies and understand the net impacts of anthropogenic activities on jaguar at large scales. DETER-B images scan the amazon every 5 days, with expectation to increase to every 2 days in near future (INPE, 2016), and are capable of identifying small scale deforestations (<7 ha). Because a measurement can be obtained weekly, it is now possible to detect and thus visit a deforestation area while its deforestation is still happening or even when it has just begun. However, enforcement incursions are often expensive, and the government might not have enough resources to visit all deforestation areas. Using the same multiplication of rasters employed in this study, it is possible to obtain daily estimation of jaguars displaced/killed in each deforestation area. This could be used to prioritize visits by enforcement agents, preferring areas with larger number of jaguars. With an indication of how many jaguars are being lost in each deforestation hotspot, they can opt to prioritize regions where more jaguars are lost. Further, the same system can be used to produce daily estimates of how many jaguars are being killed/displaced. This estimation of numbers of jaguar killed or displaced can also be used to provide a live tracker online, to inform the public of losses.

Jaguars can be conserved through a wide range of strategies and mechanisms, from government-designated protected areas to economic measures, such as reducing meat consumption, or to promoting wildlife friendly beef certification (Romero-Muñoz et al., 2020). We hope the somber estimation that around 300 jaguars are lost yearly will push the implementation of potential conservation measures forward.

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CONFLICT OF INTEREST
The authors have no conflict of interest to report.

AUTHOR CONTRIBUTIONS
Jorge F. S. Menezes wrote the first draft and performed all analysis. Fernando R. Tortato sourced the jaguar data, Luiz G. R. Oliveira-Santos, Fabio O. Roque and Ronaldo G. Morato had the idea to make the paper and contributed with comments on the manuscript.
ETHICS STATEMENT
All data in this paper was derived from other previously published studies. No animal or human experiment was involved.

DATA AVAILABILITY STATEMENT
All data used is derived from previously published sources from other authors. The current authors have no right over it.

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