Brazil’s Iguazu National Park threatened by illegal activities: predicting consequences of proposed downgrading and road construction

V M Prasniewski*, N Szinwelski, A S Bertrand, F Martello, C R Brocardo, J Cuhna, C F Sperber, R Viana, B G dos Santos, P M Fearnside and T Sobral-Souza

1 Programa de Pós-Graduação em Ecologia e Conservação da Biodiversidade, Universidade Federal do Mato Grosso, Rua Fernando Corrêa da Costa 2367, Cuiabá, 78060-900, Brazil
2 Laboratório de Orthoptera, Centro de Ciências Biológicas e da Saúde, Universidade Estadual do Oeste do Paraná, Rua Universitária 2069, Cascavel, 85819-110, Brazil
3 Instituto Mater Natura, Rua Lamenha Lins 1080 Curitiba, 80250-020, Brazil
4 Programa de Pós-Graduação em Ecologia e Manejo de Recursos Naturais, Universidade Federal do Acre, Rodovia BR 364, Km 04, Rio Branco, 69920-900, Brazil
5 Programa de Pós-Graduação em Biodiversidade, Universidade Federal do Oeste do Pará, Rua Vera Paz, Santarém, 68040-255, Brazil
6 Cuerpo de Guardaparques Nacionales, Administración de Parques Nacionales, Puerto Iguazú, Argentina
7 Departamento de Biología Geral, Universidade Federal de Viçosa, Av. PH Rolfs s/n, Viçosa, 36570-900, Brazil
8 Programa de Pós-Graduação em Biologia Neotropical, Universidade Federal da Integração Latino-Americana, Av. Tarquínio Joslin dos Santos 1000, Foz do Iguazu, 85870-901, Brazil
9 Instituto Nacional de Pesquisas da Amazônia, Av. André Araújo 2936, Manaus, 69067-375, Brazil
10 Departamento de Botânica e Ecologia, Universidade Federal do Mato Grosso, Rua Fernando Corrêa da Costa 2367, Cuiabá, 78060-900, Brazil

* Author to whom any correspondence should be addressed.

E-mail: victor.mateus.pras@gmail.com

Keywords: Atlantic Forest, Iguazu, protected areas, biodiversity, niche-based models, rainforest

Abstract
The spectacularly biodiverse Atlantic Forest of South America has been reduced to fragmented remnants. The largest remaining inland fragment is protected by national parks on either side of the iconic Iguazu Falls on the border between Brazil and Argentina. Biodiversity in the parks has been under pressure from illegal activities such as commercial hunting, fishing and extraction of palm hearts. A proposed road through Brazil’s Iguazu National Park now further threatens the area’s biodiversity by further dividing the forest fragment and by increasing access by illegal actors. Here we analyze spatial data on illegal activities and develop a niche-based model to predict the impact of the proposed Caminho-do-Colono road. The model shows the significant increases that this road would provoke in susceptibility to illegal activities such as fishing (median 0.009–0.101), palm-heart extraction (median 0.087–0.260) and poaching (median 0.324–0.334). The road proposal includes downgrading the protected status of a portion of the park, which reflects a worldwide pattern of downsizing, downgrading and degazetting protected areas that is particularly evident in Brazil.

1. Introduction
When Europeans arrived in what is now Brazil in 1500, the Atlantic Forest was 150 million ha in area (Ribeiro et al 2009), about the size of the US states of Texas and California combined. Over the succeeding centuries this rainforest was almost completely destroyed (Dean 1997), and what remains has been heavily fragmented into thousands of small (i.e. mostly <50 ha), highly degraded patches (Ribeiro et al 2009). Much biodiversity has been irrevocably lost, but what remains of the Atlantic Forest is considered to represent one of the world’s five most important biodiversity ‘hotspots’ (Myers 1988, 2003, Myers et al 2000). The largest contiguous area of inland Atlantic Forest is protected by the Iguazu
National Park in Brazil and the adjacent Iguazú National Park and Uruguaí Provincial Park in Argentina (Ribeiro et al. 2009, Rezende et al. 2018). These parks were created around the iconic Iguassu waterfalls that are shared by the two countries. Biodiversity in the parks is under pressure from a series of illegal activities, and it now faces a major threat from the proposed ‘Caminho-do-Colono’ road that would bisect the Iguazu National Park.

Biodiversity losses in many parts of the world are being accelerated by a lack of environmental legislation, enactment of laws that reduce restrictions, and policy reversals for areas that were already protected (downsizing, downgrading and degazetting, or ‘PADDD’; Bernard et al. 2014, Campos-Silva et al. 2015, de Marques and Peres 2015, Prasniewski et al. 2020). Biodiversity loss and the need for its protection are being increasingly discussed worldwide, mainly due to the role biodiversity plays in providing ecosystem services and the severe, and sometimes irreversible, social and economic impacts that biodiversity loss causes (Sala et al. 2000, 2005, Bellard et al. 2012).

Brazil’s biodiversity encompasses 8.5%–11.5% of the world’s species, yet Brazil is undergoing a severe environmental crisis with an increase in deforestation, fires and other environmental setbacks (Carvalho et al. 2019, Escobar 2019, Nobre 2019, Pereira et al. 2019, Sheikh et al. 2019, Nicolau 2020, Prasniewski et al. 2020). Illegal activities have increased due to impunity, lack of supervision and dismantlement of the country’s environmental agencies (Fearnside 2019, Ferrante and Fearnside 2019). Deforestation, logging, hunting and burning are examples of human activities harming the environment and biodiversity, resulting in defaunation and forest loss that can affect ecosystem services (Terborgh et al. 2008, Dirzo et al. 2014, Peres et al. 2016, Villar et al. 2020). Regrettably, the reporting of human illegal activities is not systematized and there are not enough law-enforcement field agents or patrols to cover all protected areas (Bertrand 2016).

An inconspicuous but important threat to biodiversity in protected areas is the unsustainable (and in most cases illegal) harvesting of wildlife and plants for human consumption. These activities, here represented by poaching, fishing and palm-heart extraction, can directly affect large endangered vertebrate species such as tapir (Tapirus terrestris), white-lipped peccary (Tayassu pecari), jaguar (Panthera onca), endemic fish species (e.g. Steindachneridion melanodermatum) and plants (e.g. Euterpae edulis). Consequently, protected areas suffer from species and/or population losses due to illegal harvesting (Galetti et al. 2017). The Brazilian National System of Protected Areas categorizes the protected areas and regulated their uses (Brazil 2000). For example, the National Forest category (IUCN category VI) allows the sustainable direct use of natural resources according to specific management plans, while the National Park category (IUCN category II) only allows indirect use, such as tourism, education and scientific research, with activities such as hunting, fishing and the harvest of timber and non-timber forest products being prohibited. Commercial and recreational hunting are either prohibited (Brazil 1967) or regulated (Brazil 1998), and all hunting, including that for subsistence, is prohibited in national parks. In Brazil, the National Council of the Environment (CONAMA 2001) regulates the management of threatened plant species in the Atlantic Forest, a biome that is also protected by federal law (Brazil 2006). Nevertheless, biodiversity continues to be threatened due to successive policy changes and the lack of enforcement of environmental regulations, as well as proposed laws that are advancing through the congressional committee processes (Brazil 2016), especially after the control of both houses of the National Congress by the ‘Centrão’ coalition, which increases the likelihood of bills like these being approved (Ferrante and Fearnside 2021).

Iguazu National Park in Brazil and the adjacent Iguazú National Park in Argentina, protect ca. 2,520 km² of inland Atlantic Forest (Ribeiro et al. 2009). This fragment hosts rich biodiversity, including rare and endangered species of fauna and flora (Crespo 1982, Straube and Urben-Filho 2004, Bertrand 2016, Brocardo et al. 2019). However, the Brazilian portion of this forest continuum is threatened by two proposed laws that change Law 9985/2000 to create a ‘parkway’ category, downgrading the status of this park from ‘integral protection’ to ‘sustainable use’. Both projects aim to create the ‘Caminho-do-Colono’ parkway, which would divide the Iguazu National Park in its currently ‘untouchable’ protected core (Prasniewski et al. 2020). Both the Brazilian and Argentinean parks are known for the iconic Iguassu waterfalls, and both are also surrounded by an agricultural and urban matrix where illegal activities abound (Bertrand 2016).

Illegal activities, such as poaching, are not randomly distributed in space, but rather are associated with rivers, roads, gentle slopes and park edges (Haines et al. 2012, Bertrand et al. 2018, Ferreguetti et al. 2018, Torres et al. 2018, Brodie and Fragoso 2020). Spatially explicit models can be used to predict these types of activities, as has been done with occupation models (Ferreguetti et al. 2018, Moore et al. 2018, Dias et al. 2020, Marescot et al. 2020). Occupation models require presence-absence data obtained by systematic sampling over space and time to estimate detectability and derive occupation values (Mackenzie et al. 2004). This requires substantial time, money and human resources for sampling. Models that use only presence data, such as niche-based models, can be very useful and easy to parameterize because inspection agencies usually already have georeferenced data on illegal activities. Niche-based models have been used to model phenomena beyond the distribution of species (Banks et al. 2006, 2013, Sobral-Souza et al. 2015,
Romero et al 2018, Guimarães et al 2020), thus, these models can be a powerful tool to spatially predict illegal activities by inferring locations (cells on the map) that are environmentally similar to locations where such activities occur, that is, how susceptible a particular location is to these activities.

We used a niche-based modeling approach to predict geographical sites susceptible to illegal activities in the Iguazu and Iguaçu National Parks to predict the possible impact that opening the ‘Caminho-do-Colono’ [CC] road would have on these activities. We hypothesized that proximity to edge, roads and rivers, in addition to flatter slopes make areas more susceptible to the following illegal activities: poaching, fishing, palm-heart extraction and establishing base camps for these activities. We also expected that the CC Road, as proposed, would increase the areas susceptible to illegal activities, further increasing the threats to biodiversity.

2. Materials and methods

2.1. Study area
The study area encompasses Iguazu National Park in Brazil (185 262 ha) and Iguaçu National Park in Argentina (67 620 ha, figure 1). Iguazu National Park is surrounded by 10 municipalities (counties) and its perimeter is immersed in a deforested matrix, while Iguaçu National Park is surrounded by three municipalities and, unlike Brazil, the matrix in which it is inserted is not predominantly deforested. Both inside and outside of both parks there are paved and unpaved roads. The parks are contained in the Iguazu watershed, which contains seven main rivers (Iguazu River, Floriano River, Gonçalves Dias River, Silva Jardim River, Belo River, Índios River and São João River) and several small rivers, terrain with varying slopes (0%-171.52%; see Environmental variables), and different types of land use and occupation, as agriculture, pastures and cities (for more information, see supplementary material available online at stacks.iop.org/ERL/17/024024/mmedia: Characteristics of the study area).

2.2. Shapefile design of the study area
The layers of geospatial information in vector format (shapefiles) for the Iguazu and Iguaçu National Parks were obtained from the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) (https://cutt.ly/cObfQjY) and Instituto Geográfico Nacional (IGN) (https://cutt.ly/MhDe5nP), respectively. The shapefiles from both parks were combined and a 500 m buffer outside the park boundaries was delimited to include illegal activities registered in forest areas linked to the continuum of both parks, known as the buffer zone (Brazil 2000, APN 2018, ICMBio 2018).

2.3. Records of illegal activities
We obtained the georeferenced records of illegal activities from the park administrations and law-enforcement agents (97.75% of records), researchers and academic research documents (2.25% of records). These records characterize the locations of illegal activities detected by law enforcement agents during inspections. Inspections were undertaken by accessing the area by car, boat or helicopter, and from the access points, travelling through the forest interior on foot for distances ranging from 3 to 15 km. For all activities, occurrence points located within the same pixel (with 100 × 100 m cell resolution) were considered as a single occurrence. Due to the diversity of infractions, we classified the records into four major groups (figure 2):

(a) Base camps: these are exactly georeferenced sites where offenders camp and often process the products of their activities. Offenders usually spend at least two or three days consecutively at these sites, and the sites are likely to be used routinely over time. Some have considerable infrastructure, with showers, meat grinders, pans and smoke houses. Activities such as poaching and fishing do not occur directly at these sites, but rather in their proximity. The camps therefore facilitate illegal activities and increase the odds of success of these activities.

(b) Poaching: sites where there was reliable and exact georeferenced evidence of poaching such as baits (known as cea by local people). At these sites there is the addition of corn (maize), manioc (cassava) or fruits to lure animals. There are also salt licks (sites with the addition of mineral salt to attract animals; known as saleiros), standing hunting (hunting at ground level, without a structure), tree hunting (hunting using platforms in trees as support, known as jiras), traps, gunshots, or sites where slaughtered animals were found.

(c) Palm-heart extraction: exactly georeferenced sites where Euterpe edulis palm hearts were extracted. Euterpe edulis was originally a widely distributed palm tree and is a key species in this biome. It occurred throughout the Atlantic Forest region and also in part of the cerrado biome. Although it still has a wide distribution, this palm tree is classified as ‘vulnerable’ by the National Center of Flora Conservation (CNCFlora 2021) because of illegal extraction.

(d) Fishing: sites with reliable and exactly georeferenced evidence of fishing such as nets, fish pots, longlines with multiple hooks, fishing rods or fish captured at the fishing site.

2.4. Environmental variables
We used four environmental variables (raster layers) in a 100 × 100 m resolution grid for all explanatory
variables that were determined using QGIS software (QGIS Development Team 2018) to predict the occurrence of illegal activities in both parks. The variables were:

(a) **Edge distance**: This represents park boundaries and reflects accessibility, and it is also close to the edge (up to 4 km) that poachers set traps or put out bait to attract animals (Wato et al 2006, Ferreguetti et al 2018). Edges can also offer escape points for offenders when the offenders see patrolling agents. Several edge lines now have cellphone signals, facilitating the communication between transgressors and informants about approaching law-enforcement forces. To estimate edge distance, we considered the limit of both parks, and we also manually drew the edges considering the fragments associated with both parks (supplementary material, figure S1). We then rasterized the edge, calculated the distance and cut the resulting raster map from the mask based on park limits and their buffers. The cells of the map assumed negative values outside the edge limits and positive values inside the limits of the delimited edge.

(b) **River distance**: this reflects accessibility (Ferreguetti et al 2018), safety (because walking along rivers leaves no traces), water for drinking, cooking and bathing, harvesting, processing and places suitable for some species targeted by hunters. Three shapefiles were used to calculate river distance: we used the shapefiles from the hydrographic web and used the main rivers provided by the Iguazu and Iguacu National Park administrations. The water mass shapefile was obtained from the Brazilian Institute of Geography and Statistics (IBGE) database (https://cutt.ly/wObg7ZS). We merged these shapefiles and deleted conflicting strokes to build the final shapefile, from which the Euclidean distance was calculated (supplementary material, figure S2).

(c) **Road distance**: this reflects accessibility, especially by vehicles or motorcycles that facilitate access or escape by offenders (Watson et al 2013, Dias et al 2020). We used two layers, one with the
Figure 2. Exact georeferenced records of illegal activities (base camps, poaching, palm-heart extraction and fishing) reported in both the Iguaçu and Iguazú National Parks.

Distance calculated using all currently existing roads (current scenario) and the other including the proposed CC road as a hypothetical future scenario. For the current scenario, we obtained the shapefile of roads from the OpenStreetMap plugin in QGIS (https://cutt.ly/RhJPADx). We considered all roads (from highways to back roads) and we also manually drew the roads not included in the plugin. To calculate the road distance considering the opening of the CC road, we used the shapefile representing the current scenario and we considered the layout of the old road based on the route provided by Prasniewski et al. (2020), saving it separately (supplementary material, figure S3). Euclidean distances were calculated from each shapefile.

(d) Slope: this reflects accessibility and is related to the ease of movement of offenders especially on the gentle slopes. However, the proximity of steep slopes can also be important because this terrain can muffle the sound of gunshots (Haines et al. 2012). We got the elevation layer from the NASA Shuttle Radar Topography Mission (SRTM) (https://cutt.ly/OhJJSBx; supplementary material, figure S4), from which the slope was calculated as a percentage, dividing the difference between the elevations of two points (rise) by the distance between them (run), then multiplied the quotient by 100. Values closed to 0 means flat slope while values higher than 60 represent very steep slopes.

2.5. Statistical analysis

2.5.1. Testing correlations and the effect of each explanatory variable on illegal activities

To test correlations between the explanatory variables, we calculated Spearman correlation with the Spearman method using the 'cor' function (stats package version 3.6.3) in the R environment (R Core Team 2020). Edges and roads showed high correlation (Pearson correlation = 0.70), and this can cause variance inflation in the models generating distorted predictions and making it impossible to separate the effects of edges and roads, so we restricted the modeling area to the location where there are roads inside the fragment, that is, the western portion of the parks (supplementary material, figure S5). This approach reduced the correlation between these variables (Pearson correlation = 0.40), enabling the dissociation of the effects of these variables and providing more reliable predictions in the scenario with the CC road.

We applied a Kolmogorov–Smirnov one-sample test using values of explanatory variables extracted from raster layers for each illegal activity to test if the observed frequency distribution was non-random. We implemented the Kolmogorov–Smirnov test using the function ‘ks.test’ (available in the R
2.5.2. Building Niche-Based Models to predict susceptibility for illegal activities

To predict the geographical sites susceptible to illegal activities in the current scenario (without the CC road) and in the hypothetical future scenario (with the CC road), we used an ensemble forecasting approach based on different mathematical algorithms. We used two classes of algorithms. The first class was presence-only algorithms, represented by the Bioclim algorithm (Nix 1986) and the Domain/Gower distance algorithm (Carpenter et al 1993). The second class was presence/pseudo-absence algorithms, represented by the support-vector machines (SVM) algorithm (Tax and Duin 2004) and the maximum entropy (MaxEnt v. 3.3.3k) algorithm (Phillips and Dudik 2008). The combined use of different algorithms creates more-reliable predictions (Barry and Elith 2006, Diniz-Filho et al 2009). All niche-based models were built with both the dismo and kernlab R packages (Karatzoglou et al 2004, Hijmans et al 2020).

All models were generated separately for each illegal activity (i.e. base camps, fishing, palm-heart extraction and poaching). After fitting, we evaluated the models by randomizing the occurrence points of each illegal activity and dividing them into two subsets (training and testing) using k-fold sampling (k = 2) with 70% of the occurrence points used for training and 30% for testing. We repeated the randomization process 100 times for each algorithm to decrease the correlation between subsets, thus generating 400 models (100 replicates × 4 algorithms) for each illegal activity. The models were built for the current scenario for the western portion of parks and projected for the entire area for both the current and the hypothetical future scenario with the CC road. We then used ensemble forecasting (Araújo and New 2007) to determine a consensus map for each illegal activity, with each cell indicating the frequency of models that predicted the presence of illegal activities in each cell. Finally, we present a map for each illegal activity, with each cell showing values ranging from 0 (low susceptibility) to 1 (high susceptibility).

2.5.3. Predicting susceptibility differences with opening of the CC road

To test whether there were significant differences in susceptibility to illegal activities after the potential CC road opening, we performed a Wilcoxon paired signed-rank test with continuity correction among values of each illegal activity in the current scenario and with opening of the CC road. This analysis was performed only for the area under influence of the road, i.e. pixels that are now closer to roads in the hypothetical scenario (CC road opened).

3. Results

Considering just the exact coordinates where illegal activities occurred and were detected, we found 882 records of illegal activities (base camps = 121, fishing = 140, palm-heart extraction = 65, poaching = 556). After removing duplicate occurrences, leaving only one occurrence per cell for each illegal activity, and dividing the area into western and eastern portions, we successfully extracted 622 records of illegal activities to build susceptibility models with (base camps = 77/18; western; fishing = 58/37; palm-heart extraction = 8/43, poaching = 260/121; figure 2). All illegal activities were most frequently closer to edges than would be expected.
if they occurred at random (figure 3), with these activities being more frequent than randomly expected in the first 2.5 km from an edge, but with the effect of edges extending up to 10 km. Except for palm-heart extraction, all illegal activities were also most frequently found closer to rivers than would be expected if their locations were random (figure 3), and these activities were more frequent than randomly expected in locations up to 500 m from rivers. Excluding base camps, all illegal activities were more associated with roads (especially in the case of distances up to 5 km) than would be expected if they occurred at random (figure 3). Finally, slope did not affect the occurrence of any illegal activity.

The ensemble frequency and the suitability consensus map for each illegal activity was built using the significant models, both inside and outside the modeling area (base camps: 227 from 400 binary maps; fishing: 108; palm-heart extraction: 23; poaching: 71). The niche-based models showed that sites closest to edges, roads and rivers were most susceptible to all illegal activities (figure 4), and if the CC road were opened, ca. 10 000 ha would be closer to roads (figure 5). Opening the CC road increased susceptibility in a fashion similar to what is currently seen in Iguazú National Park with its RN-101 road. The opening of the CC road, as suggested by the proposed laws, would increase the area susceptible to illegal activities (figure 6). Except for base camps, the areas under the influence of the road would all have significantly increased susceptibility, especially in sites that currently have low susceptibility (inside the fragment). For fishing, the median susceptibility value for illegal activities would increase from 0.009 to 0.101 with the opening of the CC road. The median for palm-heart extraction would increase from 0.087 to 0.260, and sites that currently have low susceptibility

Figure 3. Change ratio of illegal activities (base camps, fishing, palm-heart extraction and poaching) in relation to edges, rivers, road distances and slope (%) in the western region (modeling area) compared to random.
Figure 4. Predicted current susceptibility to illegal activities in the Iguazu and Iguazu National Parks. Values varies from 0 (low susceptibility) to 1 (high susceptibility).

(0.05), would have a susceptibility of 0.5 with the opening of the CC road. For poaching, the median would increase from 0.324 to 0.334, and interior sites that currently have low susceptibility (0.1) would increase their susceptibility up to 0.4 (figure 7).

4. Discussion

Our results corroborate other studies that show association of illegal activities (here represented by base camps, fishing, palm-heart extraction and poaching) with proximity to edges, roads, and rivers (Haines et al 2012, Bertrand et al 2018, Ferreguetti et al 2018, Torres et al 2018, Brodie and Fragoso 2020), but not with gentle slopes, probably because the slope variation in the region is low (7.07 ± 4.45; max = 65.06), except for the region of the Iguazu Falls, which presents an accentuated and specific relief due to falling waters (24.02 ± 20.79; max = 171.52). In general, the region is formed by gentle and crossable slopes, which are characteristics that do not significantly affect the movement of offenders. The proposed opening of the CC road would increase the incidence of illegal activities in Brazil’s Iguazu National Park because it would make more sites accessible (ca. 10000 ha). Both Argentina’s Iguazu National Park and Brazil’s Iguazu National Park are affected by the adjacent deforested landscape that is formed by chemical-intensive agriculture and by pasture and urban areas, where the park boundaries are linked to a large network of edges and roads. The accessibility promoted by edges, rivers, official roads (BR-469, RN-12 and RN-101) and by unofficial roads are the main drivers of the increase in illegal activities susceptibility in these parks. Opening the CC road would make at least 10000 ha of protected area be closer to roads, increasing this area’s susceptibility to all of the illegal activities studied here except for base camps. Roads serve as pathways for threats to biodiversity worldwide and are an important factor for calculating the human footprint in ecosystems (Venter et al 2016).

The reliability of our prediction, of an increase in the susceptibility of illegal activities (except for base camps) after opening the CC road, is corroborated by the observed frequency of illegal activity along the roads inside and outside of the Iguazu and Iguazu parks, especially the BR-469, RN-12 and RN-101 roads (see figure 4). The presence of these roads in Iguazu National Park makes almost its entire area susceptible to illegal activities (mainly fishing, palm-heart extraction and poaching). Since the models
were good enough to represent the current context of the BR-469, RN-12 and RN-101, and the models took into account the existing roads and borders along the perimeter of the parks, their prediction of future change offers a robust projection of likely negative effects in Iguazu National Park if the CC road were to be opened. The changes in susceptibility observed in the interior sites of the Iguazu National Park when we added the trajectory of the proposed CC road is exclusively due to the effect of this internal road in the region, with the edges and external roads exerting their joint effects on the perimeter of the parks. So, the opening of the CC road represents a warning of the tremendous negative effects that downgrading of fully protected areas by economic pressures and political decisions can have on protected natural areas.

4.1. Spatial context of illegal activities, ecological consequences, and management actions

The illegal activities studied here were neither evenly nor randomly distributed in space. Base camps are located far from edges (1–10 km) and the proximity of roads (0–2 km) showed a negative effect on this activity; beyond 2 km the camps are randomly distributed. This could be a strategy to avoid being detected, since the camps and signs of camps such as campfires and conversation can be more easily detected if close to edges or to roads. Alternatively, there seems to be no advantage in establishing base camps close to edges and highways because offenders can easily enter and leave the area, spending less time there and, consequently, decreasing the chances of being apprehended. The concentration of base camps near rivers reflects the basic necessity of offenders who use water for drinking, cooking, bathing and to process the bushmeat and fish obtained illegally. Rivers are also used as ‘roads’ by offenders, leaving no mark of human passage and making it difficult to locate the camps and arrest the offenders. Field operations from the Iguazu law-enforcement sector repeatedly observed this: the further from edges and roads, the more sophisticated were the base camps, which included smokehouses, many types of pans, meat grinders, tables and other items used in processing bushmeat and fish, as well as facilities for housing the offenders. The sophistication of these camps reveals that they are used for extended periods or visited periodically, enabling offenders to capture larger numbers of animals. The slope of the terrain does not affect the installation of base camps, probably because locations are chosen based on minimum requirements, such as proximity to rivers and isolation from roads, and because rough terrain does not affect the mobility of offenders over short distances.

Fishing activities necessarily occur in rivers. Rivers near edges and roads are preferred by offenders because edges and roads can reflect the aspects of accessibility, especially escape routes. Rivers close to an edge or a road enable these sites to be visited frequently, depending on the season or on
conditions that are more favorable for fishing, such as immediately after a rain, which produces cloudy waters that, for example, increase the chance of capturing some Siluriformes (Baumgartner et al. 2012, Matthews et al. 2012). Fishing was also associated with lentic rivers, which are preferred by the most-targeted endemic fish species: *Steindachneridion melanodermatum* (de Assumpção et al. 2017, ICMBio 2018). Slope does not affect fishing because it occurs in easily accessible areas (near edges and roads) or because offenders use boats, making walking and overland travel through rough terrain unnecessary.

Palm-heart extraction in both parks is directly associated with edges and roads, which provide accessibility and allow the quick flow of illegally extracted products. Offenders cut palms up to 5 km from edges and roads and transport the palm hearts to hidden locations close to an edge or a road, so neither accessibility nor movement are influenced by rough terrain. Using vehicles, usually at night, they quickly transport the palm hearts. Law-enforcement agents

---

**Figure 6.** Predicted impact of the opening the CC road in Iguaçu National Park in terms of susceptibility to illegal activities and the difference between them. Predictions values vary from 0 (low susceptibility) to 1 (high susceptibility) while difference values varies from −1 (susceptibility decrease) to 1 (susceptibility increase).
in both parks have reported up to 200 palm hearts apprehended at a single location and areas within the parks where more than 500 palms have been cut. Palm hearts are generally extracted in large quantities, and areas with large cuts are commonly found in both parks, increasing the pressure on this vulnerable species (CNCFlora 2021). The extensive perimeters of the parks make enforcement activities a major challenge (Bertrand et al. 2018). River proximity did not influence palm-heart extraction, which was a surprise given that law enforcement agents report the use of boats for undertaking this activity. However, this may be due to the relatively low frequency of palm-heart extraction detections in the modelled area (8) compared to the predicted area (43), although palm hearts occur throughout the parks.

Poaching was often reported as associated with proximity to edges, roads and rivers, and this may indicate that offenders live close by and visit these locations whenever they feel safe. Because these locations are easily accessible, they both allow a quick escape and reduce the time spent in obtaining hunted animals. Poachers can also come from afar, using vehicles to transport their products. Poaching associated with water bodies reflects the fact that the strategies of offenders are based on the biology of target animals (Ferreguetti et al. 2017, Dias et al. 2020). Some species (such as Cuniculus paca, Hydrochoerus hydrochaeris, Tayassu pecari and Tapirus terrestris) use habitats more frequently near waterbodies (Mones and Ojati 1986, Reyna-Hurtado et al. 2009, Ferreguetti et al. 2017, 2018). Poachers build perches in trees that allow them to wait and shoot these animals as they approach the waterbodies. The non-significant influence of the slope of the terrain on the choice of poaching sites can be explained mainly by ease of movement in the region, mainly formed by flatter areas. This benefits poachers because they usually carry heavy items, such as water, weapons, and other supplies, and because they also must bring back the product of their activities (animals or their parts).

These illegal activities undoubtedly generate consequences for biodiversity and ecological processes. Poaching impacts fauna in both parks, reducing animal populations, and disturbing the ecological balance (Paviolo et al. 2009, Bertrand 2016, da Silva et al. 2018). For example, Tayassu pecari has its population reduced in Iguazú National Park (Paviolo et al. 2008) and this species has been locally extinct for twenty years in Iguaçu National Park (Brocardo et al. 2017). Loss of this species, which acts as an 'ecosystem engineer', impacts the plant community (Villar et al. 2020), nutrient cycles (Villar et al. 2021) and the size of top predator populations (Paviolo et al. 2008). This also increases conflict between jaguars and cattle ranchers in the Iguaçu region; in the 1990s this conflict was attributed to the low availability of natural prey (de Azevedo 2008). Additionally, the decline of large animals, which are preferred by poachers (Fragoso et al. 2011), may impact recruitment of zoochoric plants (Fadini et al. 2009), plant gene flow (Giombini et al. 2017) and the carbon-sink capacity.
of the forest (Bello et al 2015). Areas with palm-heart extraction have their Euterpe edulis densities decreased by up to 8 times, reducing seed and food availability and impacting animal species richness (Muler et al 2014). Overfishing impacts fish populations, skewing the size distributions of individuals and the composition of the aquatic food web (Allan et al 2005). In the Iguazu River, fishing is concentrated on Steindachneridion melanodermatum, which may give this activity a particularly pernicious impact on the whole fish community because this fish species is endemic to the lower Iguazu River and some of its tributaries (Garavello 2005) and because the main population is concentrated within the parks (de Assumpção et al 2017).

The high number of illegal activities and their consequences reported here highlight the urgent need to mitigate and reduce illegal activities in these protected areas. To achieve this goal, understanding the spatial distribution of illegal activities in protected areas can provide valuable information both for understanding how offenders behave and for providing input for law-enforcement strategies. When decision makers and law-enforcement agents know the areas that are most susceptible to infractions, they can develop more-effective strategies for patrols. Long-term actions can also be planned, such as the construction of surveillance posts, campaigns, and socioenvironmental projects to raise awareness among the population adjacent to the parks. It is fundamental to rely on scientific assessments rather than political or economic interests when suggesting the opening of roads and other so-called ‘development’ projects inside or close to protected areas, since the impacts on fauna and flora may be both irreversible and economically disastrous. Such considerations must substantiate the environmental legislation of both countries and the management plans for their protected areas.

4.2. Road effects in susceptibility to illegal activities

Roads are an important factor in structuring natural populations and communities. Because sites close to the roads are more accessible, they have greater depletion of target species. Consequently, roads can have additive or worsening effects such as fragmentation (Laurance et al 2018), population isolation (Laurance et al 2009) and changes in microclimate and soil (Delgado et al 2007). Opening the CC road will not accentuate the already established edge effect because no edge will be created with the CC opening, but it will accentuate the deleterious effect of roads in protected areas, especially in the western part of the park, which is narrower and, if the opening were to be approved, this region would be separated from the most-preserved portion of the park. Area close to roads maintain less vertebrate richness and harbor lower numbers of threatened species than do large areas without roads (Pfeifer et al 2017), such as is Iguazu National Park in its current state. Additional negative effects of roads on these natural environment include alteration of nutrient cycling and release of greenhouse gases (Truscott et al 2005, Lee et al 2012), as well as limiting the movement of many species (Andrews 1990, Andrews and Gibbons 2005), isolating populations (Laurance et al 2000) and reducing genetic diversity (Holderegger and Di Giulio 2010). The CC road can increase the roadkills of both vertebrates and invertebrates (Andrews 1990), besides acting as a facilitator of biological invasion, which is a growing problem in the biodiversity hot-spot where the parks are located (i.e. the Atlantic Forest; Bellard et al 2014). For instance, researchers and law-enforcement agents found 15 exotic plant species in and around a road used for tourism in the Iguazu National Park (Rodolfo et al 2008). The CC Road can also facilitate logging, fires and all types of smuggling, invasions for agriculture and pasture, and extraction of minerals and forest products (Laurance et al 2002, 2009, Adeney et al 2009). A major road that cuts through the core of a protected area would bring the worst of these effects, impairing biodiversity and its associated ecosystem services and contradicting the protected area’s main objective of biodiversity conservation. This is even more worrying because the Iguazu National Park is the last and largest remnant of inland Atlantic Forest under protection (Ribeiro et al 2009). Opening the CC road would destroy part of this irreplaceable ecosystem.

There are many social, cultural and economic pressures behind the proposal to open the CC road: people claim that their right to come and go has been undermined, that their previous commercial and personal relations with both sides of the park (Capanema and Serranópolis do Iguacu, in particular), have been forgotten and that their freedom has been taken away. Arguments for the road emphasize the costs of transportation between the western and southwestern portions of the state of Paraná, which would be easier because of the shorter distance to be traveled if passing through the park. Alternative suggestions that integrate the socio-cultural-economic context for implementation of the CC road are presented in Prasniewski et al (2020).

Those arguing for opening the CC road often refer to the presence of Highway BR-469 at the western end of Iguazu National Park, which gives access to the Iguassu Falls. However, BR-469 meets the criterion of a ‘parkway’, which is for roads that provide access to areas with extraordinary beauty, taking into account their cultural, economic, touristic, entertainment and educational importance (Carr 1998), as contrasted with the CC road’s function of linking cities or diminishing the costs of transportation.

We have shown that all highways or roads that are built in conservation units result in high rates of
sustainability causes soil compaction and water pollution that can extend into the food web through bioaccumulation (Dawson 2008). Conservation units cut by roads, such as the Taim Ecological Station (Rio Grande do Sul, Brazil), which is crossed by BR-471 and Sooretama Biological Reserve (Espírito Santo, Brazil), which is crossed by BR-101, show alarming roadkill rates (da Rosa and Bager 2012, Bager and Fontoura 2013, Klippel et al 2015, Srbek-Araujo et al 2015). This also happens on the currently existing roads in the Iguacu and Iguazu parks. Although roadkill monitoring is not yet fully systematized, there were numerous records of threatened species being run over, such as Panthera onca, Leopardus pardalis, Sylvilagus brasiliensis and Mazama americana, among other vertebrates (Brocardo et al 2019). Since 2016, a research project has been underway on the Brazilian side regarding roadkill mitigation, but the results have not yet been published. Opening the CC road for transportation purposes would add roadkill to the other environmental impacts of the road.

4.3. Effect of precipitated political decisions and implications for other parks

The effect of rash or negligent policy decisions on environmental issues can have severe and irreversible effects on ecosystems. Discussion and evaluation of the risks of certain environmental actions therefore need to be based on prior scientific studies and extensive discussion with local communities. This is lacking in Brazil. Proposed laws usually stem from promises made in political campaigns and aim to favor lobbies and financial groups, neglecting the universal principle described in Article 255 of the Brazilian constitution: ‘Everyone has the right to an ecologically balanced environment and a shared use of the people that is essential for a healthy quality of life, imposing on the public authorities and the community the duty to defend and preserve it for present and future generations’ (Brazil 1988; free translation). Throughout the world there are many proposals for protected-area downgrading, downsizing and degazettement (PADD). More than 3700 PADD events have been reported globally, of which 90 are in Brazil, affecting 110 000 km² (CI and WWF 2019; see www.paddtracker.org for more information). The downgrading proposal that is underway for Iguacu National Park means that the government intends to legally decrease restrictions on human activities in this conservation area despite its being a reference for conservation in the country. It is evident that the reasons for PADD in general are strictly political and economic (e.g. mining, agriculture, transportation and extraction of forest products) rather than serving cultural, social or conservation purposes.

4.4. Potential of ecological niche models for monitoring, prediction and political decisions on illegal activities

Our results demonstrate that niche-based models are useful tools for studying phenomena that go far beyond the ecological niches of species, as reported in other studies (Banks et al 2006, 2013, Sobral-Souza et al 2015, Romero et al 2018, Guimaraes et al 2020). Our models presented spatial patterns similar to those found by authors who used presence-absence data to predict illegal activities (Ferreguetti et al 2018, Moore et al 2018, Dias et al 2020, Maresco et al 2020). For example, predictive hunting models based on detectability generated the same spatial pattern as historical presence-only hunting data, i.e. when using presence-only data to model poaching, the authors found spatial patterns like those from models using detectability data (Ferreguetti et al 2018). Additionally, to get true absence for illegal activities is arduous due to the offenders’ behavior, which includes deliberately covering up their tracks and stealing monitoring equipment.

We have demonstrated that the susceptibility model can be a powerful and agile tool for predicting the spatial distribution of sites susceptible to illegal activities in conservation areas and for predicting the impacts of political decisions (such as PADD and opening roads). Georeferenced information on the occurrences of these activities is required for correctly fitting the models. Data of this type are available in databases around the world, so this tool can be validated based on new studies and can be used to guide law-enforcement, conservation, and management measures in the short, medium, and long terms.

5. Conclusions

Brazil’s Iguacu National Park is currently subject to substantial impacts from illegal hunting, fishing and palm-heart extraction, and these impacts would increase if the park were to be bisected by a proposed road. These activities impact biodiversity in the largest remaining remnant of inland Atlantic Forest which is a global biodiversity ‘hotspot’. A niche-based model shows the magnitude of the increase in illegal activities, indicating the high environmental cost that the road would have. The model also identifies the locations of probable increases in illegal activity, providing valuable information for law-enforcement. However, the benefits of the study for law-enforcement would not compensate for the high impact of the proposed road, which the results suggest should not be built. The modeling tools developed in this study can be applied to many similar situations elsewhere, both for improving environmental control and for projecting impacts of infrastructure proposals before decisions are made.
Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

We thank all scientists, law-enforcement field agents and conservationists who contributed information for our manuscript. Due to the risk of political and social retaliations we cannot name some of them. We also thank Ana T B Guimarães for statistical and computational support and Ariel (patrol Argentina) and Adaildo Policena for information on field activities. VMP thanks CNPq for a doctoral fellowship (Process 141645/2020-2). PMF thanks CNPq (Process 31103/2015-4). CFS thanks CNPq (Process 310353/2019-0). NS thanks Fundação Araucária (Edital 09/2021).

ORCID iDs

V M Prasniewski https://orcid.org/0000-0001-9783-9328
N Szinwelski https://orcid.org/0000-0003-4049-3121
A S Bertrand https://orcid.org/0000-0002-8212-2524
F Martello https://orcid.org/0000-0003-1243-9750
C R Brocardo https://orcid.org/0000-0003-3142-5688
J Cuhna https://orcid.org/0000-0002-3941-0753
C F Sperber https://orcid.org/0000-0002-0334-7216
R Viana https://orcid.org/0000-0002-4235-4048
B G dos Santos https://orcid.org/0000-0001-7923-9097
P M Fearnside https://orcid.org/0000-0003-3672-9082
T Sobral-Souza https://orcid.org/0000-0002-2367-2315

References

Adeney J M, Christensen Jr N L and Pimm S L 2009 Reserves protect against deforestation fires in the Amazon PLos One 4 e5014
Allan J D, Abell R, Hogan Z, Revenga C, Taylor B W, Welcomme R L and Winemiller K 2005 Overfishing of inland waters BioScience 55 1041–51
Andrews A 1990 Fragmentation of habitat by roads and utility corridors: a review Aust. Zoolologist 26 130–41
Andrews K M and Gibbons J W 2005 How do highways influence snake movement? Behavioral responses to roads and vehicles Copeia 2005 772–82
APN 2018 Administración de Parques Nacionales Plan de Gestión Parque Nacional Iguazú Periodo 2017-2023 (Ministerio de Ambiente y Desarrollo Sustentable y Administración de Parques Nacionales, Buenos Ayres)
Araújo M B and New M 2007 Ensemble forecasting of species distributions Trends Ecol. Evol. 22 42–7
Bager A and Fontoura V 2013 Evaluation of the effectiveness of a wildlife roadkill mitigation system in wetland habitat Ecol. Eng. 53 31–8
Banks W E et al 2006 Eco-cultural niche modeling: new tools for reconstructing the geography and ecology of past human populations PaleoAnthropology 2006 68–83
Banks W E, Antunes N, Rigaud S and D’Errico F 2013 Ecological constraints on the first prehistoric farmers in Europe J. Archaeol. Sci. 40 2746–53
Barry S and Elith J 2006 Error and uncertainty in habitat models J. Appl. Ecol. 43 413–23
Baumgartner G, Pavaneli C S, Baumgartner D, Bifi A G, Debona T and Frana V A 2012 Peixes do baixo rio Iguazu (Paraná: Eduem)
Bellard C, Bertelsmeier C, Leadley P, Thuiller W and Courchamp F 2012 Impacts of climate change on the future of biodiversity Ecol. Lett. 15 365–77
Bellard C, Leclerc C, Leroy B, Bakkenes M, Velos S, Thuiller W and Courchamp F 2014 Vulnerability of biodiversity hotspots to global change Glob. Ecol. Biogeogr. 23 1376–86
Bello C, Galetti M, Pizo M A, Magnago L F S, Rocha M F, Lima R A, Peres C A, Ovaskainen O and Jordano P 2015 Defaunation affects carbon storage in tropical forests Sci. Adv. 1 1–11
Bernard E, Penna L A O and Araújo E 2014 Downgrading, downsizing, degazettement and reclassification of protected areas in Brazil Conserv. Biol. 28 939–50
Bertrand A S 2016 Characterization and conservation of the Iguazu National Park, Brazil PhD Thesis University of Aveiro, Portugal
Bertrand A S, Garcia J C, Baptiston I C, Esteves E and Nauderer R 2018 Characterization preliminar de caça furtiva no Parque Nacional do Iguazu (Paraná) Biodivers. Bras. 8 19–34
Brazil 1967 Lei N2 5.197, de 3 de JANEIRO de 1967, Dispõe sobre a Política Nacional de Fauna e de Caça e dá outras providências Diário Oficial da União, Seção 1, Página 177, Brasília - DF (available at: http://www.planalto.gov.br/ccivil_03/leis/l5197.htm)
Brazil 1988 Constituição da República Federativa do Brasil Senate Federal: Centro Gráfico, Brasília - DF
Brazil 1998 Lei N2 9.605, de 12 de fevereiro de 1998Dispõe sobre as sanções penais e administrativas derivadas de condutas e atividades lesivas ao meio ambiente e dá outras providências Diário Oficial da União, Coluna 1, Página 1, Brasilia - DF (available at: www.planalto.gov.br/ccivil_03/leis/9605.htm)
Brazil 2000 Lei N2 9.985, de 18 de julho de 2000, Regulamenta o art. 225, § 1o, incisos I, II, III e VII da Constituição Federal, institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências Diário Oficial da União, Seção 1, Página 1, Brasilia - DF (available at: www.planalto.gov.br/ccivil_03/leis/9985.htm)
Brazil 2006 Lei N2 11.428, de 22 de dezembro de 2006, Dispõe sobre a utilização e proteção da vegetação nativa do Bvima Mata Atlântica, e dá outras providências Diário Oficial da União, Seção 1, Página 1, Brasilia - DF (available at: www.planalto.gov.br/ccivil_03/leis/11428.htm)
Brazil 2016 Câmara dos Deputados Projeto de lei 6268/2016, Dispõe sobre a Política Nacional de Fauna e dá outras providências, Projeto de autoria do Sr. Valdir Colatto, Brasilia - DF (available at: www.camara.leg.br/propostas-legislativas/2113552)
Brocardo C R et al 2019 Mamíferos do Parque Nacional do Iguazu Oecol. Aust. 23 165–90
Brocardo C R, da Silva M X, Delgado L E and Galetti M 2017 White-lipped peccaries are recorded at Iguazu National Park after 20 years Mammutia 81 519–22
Brodie J F and Fragozo J M 2020 Understanding the distribution of bushmeat hunting effort across landscapes by testing hypotheses about human foraging Conserv. Biol. 35 1009–18
Campos-Silva J V, Ferreira S and Augusto C 2015 Policy reversals do not bode well for conservation in Brazilian Amazonia Nat. Conserv. 3 193–5

Carpenter G, Gillison A N and Winter J 1993 DOMAIN: a flexible modelling procedure for mapping potential distributions of plants and animals Biodivers. Conserv. 2 667–80

Carr E 1998 Wilderness by Design: Landscape Architecture and the National Park Service (Lincoln, NE: University of Nebraska Press)

Carvalho W D, Mustin K, Hilário R R, Vasconcelos I M, Eikers V and Fearnside P M 2019 Deforestation control in the Brazilian Amazon: a conservation struggle being lost as agreements and regulations are subverted and bypassed Perspect. Ecol. Conserv. 17 122–30

CNCFlora, Centro Nacional de Conservação da Flora 2021 Euterpe edulis in Lista Vermelha da flora brasileira versão 2012.2 (available at: http://cncflora.jbrj.gov.br/portal/pt-br/profile/Euterpe-edulis)

CONAMA, Conselho Nacional de Meio Ambiente 2001 Resolução CONAMA N° 278, de 24 de maio de 2001 Dispõe contra corte e exploração de espécies ameaçadas de extinção da flora da Mata Atlântica Diário Oficial da União, Página 51-52, Brasília—DF (Available at: http://www2.mma.gov.br/port/conama/legislt/cfm/logid=276)

Conservation International and World Wildlife Fund 2019 Data Release Version 2.0 (Version 2.0) [Data set] (available at: PAID2Tracker.org)

Crespo J A 1982 Ecologia de la comunidad de mamíferos del parque nacional Iguazu, Misiones Rev. Museo Argentino Cie. Nat. Ecol. 3 45–162

da Rosa C A and Bager A 2012 Seasonality and habitat types affect roadkill of neotropical birds J. Environ. Manage. 97 1–5

da Silva M X, Paviliole A, Tambolesi L R and Pardini R 2018 Effectiveness of protected areas for biodiversity conservation: mammary occurrence patterns in the Iguacu National Park. Brazil J. Nat. Conserv. 41 51–62

Dawson T M 2008 Water in Road Structures Movement, Drainage and Effects (Berlin: Springer Science & Business Media)

de Assumpção L, Makrakis S, da Silva P S and Makrakis M C 2017 Espécies de peixes ameaçadas de extinção no Parque Nacional do Iguacu Biodivers. Bras. 7 4–17

de Azevedo F C C 2008 Food habits and livestock depredation of sympatric jaguars and pumas in the Iguacu National Park area, south Brazil Biota tropica 40 494–508

de Marques A A B and Perez C A 2015 Pervasive legal threats to protected areas in Brazil Orya 49 25–9

Dean W 1997 With Broadax and Firebrand: The Destruction of the Brazilian Atlantic Forest (Berkeley, CA: University of California Press)

Delgado J D, Arroyo N L, Arévalo J R and Fernández-Palacios J M 2007 Edge effects of roads on temperature, light, canopy cover and canopy height in laurel and pine forests (Tenerife, Canary Islands) Landscape Urban Plan. 81 328–40

Dias D d M, Fearnside P M and Rodrigues F H G 2020 Using an occupancy approach to identify poaching hotspots in protected areas in a seasonally dry tropical forest Biol. Conserv. 251 1–8

Diniz-Filho J A F, Mauricio Bini L, Fernando Rangel T, Loyola R D, Hof C, Noguez-Bravo D and Araujo M B 2009 Partitioning and mapping uncertainties in ensembles of forecasts of species turnover under climate change Ecography 32 897–906

Dirzo R, Young H S, Galetti M, Ceballos G, Isaac N J B and Collen B 2014 Defaunation in the Anthropocene Science 345 401–6

Escobar H 2019 Brazil’s deforestation is exploding—and 2020 will be worse (available at: www.sciencemag.org/news/2019/11/brazil-s-deforestation-exploding-and-2020-will-be-worse)

Farabbini R F, Fleury M, Donatti C I and Galetti M 2009 Effects of frugivore impoverishment and seed predators on the recruitment of a keystone palm Acta Oecol. 35 188–96

Fearnside P M 2019 Brazilian Amazon deforestation surge is real despite Bolsonaro’s denial (commentary) (available at: https://news.mongabay.com/2019/07/brazilian-amazon-deforestation-surge-is-real-despite-bolsonaros-denial-commentary/)

Ferrante L and Fearnside P M 2019 Brazil’s new president and ‘ruralists’ threaten Amazonia’s environment, traditional peoples and the global climate Environ. Conserv. 46 261–3

Ferrante L and Fearnside P M 2021 Brazil’s political upset threatens Amazonia Science 371 898

Ferreugetti A C, Pereira-Ribeiro J, Prevedello J A, Tomás W M, Rocha C D F and Bergallo H G 2018 One step ahead to predict potential poaching hotspots: modeling occupancy and detectability of poachers in a neotropical rainforest Biol. Conserv. 227 133–40

Ferreugetti A C, Tomás W M and Bergallo H G 2017 Density, occupancy and detectability of lowland tapisirí Tapirus terrestris, in Vale Natural Reserve, southeastern Brazil J. Mammal. 98 114–23

Fragoso R d O, Delgado L E d S and Lopes L d M 2011 Aspectos da atividade de caça no Parque Nacional do Iguazu, Paraná Rev. Biol. Neotropical 8 41–52

Galetti M et al 2017 Defaunation and biomass collapse of mammals in the largest Atlantic forest remnant Animal Conserv. 20 270–81

Garavello J C 2005 Revision of genus Steindachneridion (Siluriformes: Pimelodidae) Neotropical Ichthyol. 3 607–23

Giombini M I, Bravo S P, Sica Y V and Tosto D S 2017 Early genetic consequences of defaunation in a large-seeded vertebrate-dispersed palm (Syagrus romanzoffiana) Heredity 118 568–77

Guimarães A, da Silva P H, Carneiro F M and Silva D P 2020 Using distribution models to estimate blooms of phytosanitary cyanobacteria in Brazilian Biota Neotropical 20 e20190756

Haines A M, Elledge D, Wilking E K, Grabe M, Barke M D, Burke N and Webb S L 2012 Spatially explicit analysis of poaching activity as a conservation management tool Wildlife Soc. Bull. 36 685–92

Hijmans R J, Phillips S, Leathwick J and Elith J 2020 Package dismo (available at: https://cran.r-project.org/web/packages/dismo/dismo.pdf)

Holderegger R and Di Giulió M 2010 The genetic effects of roads: a review of empirical evidence Basic Appl. Ecol. 11 522–31

ICMBio - Instituto Chico Mendes de Conservação da Biodiversidade. 2018 Plano de Manejo do Parque Nacional do Iguazu (Brasilia: Ministério do Meio Ambiente)

Karatzoglou A, Smola A, Hornik K and Zeileis A 2004 A survey on patents of typical robust image watermarking Adv. Mater. Res. 11 1–20

Klippe H A, Oliveira P V, Britto K B, Freire B F, Moreno M R, dos Santos A R, Banhos A and Paneto G G 2015 Using DNA barcodes to identify road-killed animals in two atlantic forest nature reserves, Brazil PLoS One 10 1–15

Laurance W F et al 2002 Ecosystem decay of Amazonian Forest fragments: a 2-year investigation Conserv. Biol. 16 605–18

Laurance W F, Camargo J L C, Fearnside P M, Lovejoy T E, Williamson G B, Mesquita R C G, Meyer C F J, Bobrowiec P E D and Laurance S G 2018 An Amazonian rainforest and its fragments as a laboratory of global change Biol. Rev. 93 223–47

Laurance W F, Delamonica P, Laurance S G, Vasconcelos H L and Lovejoy T E 2000 Rainforest fragmentation kills big trees Nature 404 836

Laurance W F, Goosman M and Laurance S G 2009 Impacts of roads and linear clearings on tropical forests Trends Ecol. Evol. 24 659–69

Lee M A, Davies L and Power S A 2012 Effects of roads on adjacent plant community composition and ecosystem function: an example from three calcareous ecosystems Environ. Pollut. 163 273–80

Liu C, Newell G and White M 2016 On the selection of thresholds for predicting species occurrence with presence-only data Ecol. Evol. 6 337–48
Mackenzie D I, Bailey L L and Nichols J D 2004 Investigating species co-occurrence patterns when species are detected imperfectly J. Animal Ecol. 73 546–55
Marescot L, Lyet A, Singh R, Carter N and Gimenez O 2020 Inferring wildlife poaching in southeast Asia with multispecies dynamic occupancy models Ecography 43 239–50
Masanjo G F 2014 Human population growth and wildlife extinction in Ugalá ecosystem, western Tanzania J. Sustain. Dev. Stud. 5 192–217
Matthews W J 2012 Patterns in Freshwater Fish Ecology (Berlin: Springer Science & Business Media)
Mones A and Ojati J 1986 Hydrochoerus hydrochaeris Mamm. Species 264 1–7
Moore J P, Mulindahabi F, Masozera M K, Nichols J D, Hines J E, Turkunkéko E and Ol D M K 2018 Are ranger patrols effective in reducing poaching-related threats within protected areas? J. Appl. Ecol. 55 99–107
Muler A E, Rother D C, Brancalion P S, Naves R P, Rodrigues R R and Pizo M A 2014 Can overharvesting of a non-timber-forest-product change the regeneration dynamics of a tropical rainforest? The case study of Euterpe edulis Forest Ecol. Manag. 324 117–25
Myers N 1988 Threatened biotas: hot spot in tropical forests Environmentalist 8 187–222
Myers N 2003 Biodiversity hotspots revisited Bioscience 53 916–17
Myers N, Mittermeier R A, Mittermeier C G, da Fonseca G A B and Kent J 2000 Biodiversity hotspots for conservation priorities Nature 403 853–8
Nicola V 2020 Amazon’s wildfire season will coincide with peak of pandemic, warns specialist (available at: www.brasildefato.com.br/2020/06/12/amazon-s-wildfire-season-will-coincide-with-peak-of-pandemic-specialist)
Nix H A 1986 A biogeographic analysis of Australian elapid snakes Atlas Elapida Snakes Aust. 7 4–15
Nobre C A 2019 To save Brazil’s rainforest, boost its science Nature 574 455
Paviolo A, de Angelo C D, di Blanco Y E and di Bitetti M S 2008 Jaguar Panthera onca population decline in the Upper Paraná Atlantic Forest of Argentina and Brazil Oryx 42 554–61
Paviolo A, de Angelo C, di Blanco Y, Agostini I, Pizzio E, Melzaw R, Ferrari C, Palacio L and Di Bitetti M S 2009 Efeito da caça e nível de proteção em a abundancia dos grandes mamíferos do Bosque Atlântico de Misiones Parque Nacional Iguazu, Conservación y Desarrollo en la Selva Paranaense de Argentina (Administración de Parques Nacionales, Buenos Aires)
Pearson R G, Raxworthy C J, Nakamura M and Peterson A T 2007 Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar J. Biogeogr. 34 102–17
Pereira E J d L, Fereira P J S, Ribeiro L C d S, Carvalho T S and Pereira H B d B 2019 Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest Environ. Sci. Policy 100 8–12
Peres C A, Emilio T, Schietti J, Desmoulière S J and Levi T 2016 Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests Proc. Natl. Acad. Sci. USA 113 892–7
Pfeifer M et al 2017 Creation of forest edges has a global impact on forest vertebrates Nature 551 187–91
Phillips S J and Dudik M 2008 Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation Ecography 31 161–75
Prasniowski V M, Szinelski N, Sobral-Souza T, Kuczach A M, Brocardo C R, Sperber C F and Fernsarp M 2020 Parks under attack: Brazil’s Iguacu National Park illustrates a global threat to biodiversity Ambio 49 2061–7
QGIS Development Team 2018 QGIS Geographic Information System. Version 3. 14.16-Pi (Open Source Geospatial Foundation)
R Core Team 2020 R: a language and environment for statistical computing (available at: www.r-project.org/)
Reyna-Hurtado R, Rojas-Flores E and Tanner G W 2009 Home range and habitat preferences of white-tipped pecarys (Tayassu pecari) in Calakmul Campeche, Mexico J. Mammm. 90 1199–209
Rezende C L, Scarno F R, Assad E D, Joly C A, Metzger J P, Strassburg B N, Tabarelli M, Fonseca G A and Mittermeier R A 2018 From hotspot to hotsopost: an opportunity for the Brazilian Atlantic Forest Perspect. Ecol. Conserv. 16 208–14
Ribeiro M C, Metzger J P, Martensen A C, Ponzoni F J and Hirota M M 2009 The Brazilian Atlantic Forest: how much is left and how is the remaining forest distributed? Implications for conservation Biol. Conserv. 142 1141–53
Rodolfo A M, Temponi L G and Cândido-Jr J F 2008 Levantamento de plantas exóticas na trilha do Poço, Parque Nacional do Iguacu, Paraná, Brasil Rev. Brus. Biotec. 6 23–30
Romero G Q, Gonçalves-Souza T, Kratina P, Marino N A C, Petry W K, Sobral-Souza T and Roslin T 2018 Global predation pressure redistribution under future climate change Nat. Clim. Change 8 1087–93
Sala O E et al 2000 Global biodiversity scenarios for the year 2100 Science 287 1770–4
Sala O E et al 2005 Biodiversity across Scenarios Ecosystems and Human Well-Being: Scenarios. Findings of the Scenarios Working Group, ed S R Carpenter (Washington, DC: Island Press) pp 375–408
Sheikh P A, Meyer P J, Procita K and Hoover K 2019 Fire and deforestation in the Brazilian Amazon (available at: https://fas.org/sgp/crs/row/IF11306.pdf)
Sobral-Souza T, Lima-Ribeiro M S and Solféroni V N 2015 Biogeography of neotropical rainforests: past connections between Amazon and Atlantic Forest detected by ecological niche modeling Ecol. Evol. 5 43–55
Staub F C and Urben-Filho A 2004 Uma revisão crítica sobre o grau de conhecimento da avifauna do Parque Nacional do Iguacu (Paraná, Brasil) e áreas adjacentes Atualidades Ornitológicas 113 1–26
Tax D M J and Dunn R P W 2004 Support vector data description J. Mamm. 55 45–66
Terborgh J, Nuñez-Iturri G, Pitman N C A, Valverde F H, Alvarez P, Swamy V, Pringle E G and Paine C E T 2008 Tree recruitment in an empty forest Ecology 89 1757–68
Torres P C, Morsello C, Parry L, Barlow J, Ferreira J, Gardner T and Pardini R 2018 Landscape correlates of bushmeat consumption and hunting in a post-frontier Amazonian region Environ. Conserv. 45 352–60
Truscott A M, Palmer S C, McGowan G M, Cape J N and Kent J 2000 Biodiversity hotspots for conservation priorities for the Earth’s biota Nature 403 853–8
Venter O et al 2016 Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation Nat. Commun. 7 1–11
Villar N, Paz C, Zipparro V, Nazareth S, Bulascoschi L, Bakker E S and Galetti M 2021 Frugivory underpins the nitrogen cycle
Funct. Ecol. 35 357–68

Villar N, Siqueira T, Zipparro V, Farah F, Schmaedecke G, Hortenci L, Brocardo C R, Jordano P and Galetti M 2020
The cryptic regulation of diversity by functionally complementary large tropical forest herbivores
J. Ecol. 108 279–90

Wato Y A, Wahungu G M and Okello M M 2006 Correlates of wildlife snaring patterns in Tsavo West National Park, Kenya
Biol. Conserv. 132 500–9

Watson F, Becker M S, McRobb R and Kanyembo B 2013 Spatial patterns of wire-snare poaching: implications for community conservation in buffer zones around National Parks
Biol. Conserv. 168 1–9