

CONTRIBUTED PAPER

High-resolution drone imagery reveals drivers of fine-scale giant otter habitat selection in the land-water interface

Nicole Abanto Valladares^{1,2} | Alejandro Alarcon Pardo² | Luca Chiaverini¹ |
Jessica Groenendijk² | Lauren A. Harrington¹  | David W. Macdonald¹ |
Ronald R. Swaisgood³ | Adi Barocas^{1,2,3} 

¹Wildlife Conservation Research Unit,
Department of Zoology, The Rezanati-
Kaplan Centre University of Oxford,
Abingdon, UK

²Giant Otter Conservation Program, San
Diego Zoo Global Peru, Cusco, Peru

³Recovery Ecology, San Diego Zoo
Wildlife Alliance, Escondido,
California, USA

Correspondence

Adi Barocas, Recovery Ecology, San Diego
Zoo Wildlife Alliance, 15600 San Pasqual
Valley Road, Escondido, CA 92027, USA.
Email: adibarocas@gmail.com

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Abstract

Neotropical freshwater habitats are particularly sensitive to degradation by human activity. Piscivorous semi-aquatic freshwater megafauna inhabit both the terrestrial and aquatic mediums and thus may be good indicators of wetland habitat quality. However, the drivers of their space use at the terrestrial and aquatic landscape levels are not well understood. We studied the spatial behavior and habitat use of giant otters in Madre de Dios, Peru, inhabiting areas with variable levels of protection. We combined unmanned aerial vehicle (UAV) and satellite images to develop different terrestrial and water-associated land cover variables. We tested the influence of these predictors on giant otter habitat use at multiple spatial scales, comparing used and available locations. Giant otters favored bank areas with dense forest canopy cover. In the aquatic medium, giant otters showed positive selection for open water and fallen logs and avoided floating vegetation. These findings may be explained by preference for optimal fish habitat to maximize foraging yield and bank areas that provide more cover from predators and higher quality denning locations. Variables developed from UAV images outperformed satellite-derived variables. Despite recent signs of deforestation in lake banks in unprotected areas, spatial model predictions indicated that unprotected oxbow lakes did not differ in their habitat suitability from protected freshwater habitats. Management implications of our findings include identification of factors driving habitat suitability to guide policy and decisions regarding protection or restoration of oxbow lake ecosystems to support giant otter populations. In addition, we demonstrate that UAVs have value in complementing satellite-derived images and providing a cost-effective methodology to assess habitat quality for semi-aquatic species at the land-water interface.

KEYWORDS

habitat degradation, habitat selection, remote-sensing, satellite, UAVs, umbrella species, wetlands

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1 | INTRODUCTION

Freshwater ecosystems are particularly vulnerable to the effects of human activities through land transformation by the construction of dams, mining, land-cover change, and global climate change, especially in the neotropics (Carpenter et al., 2011). These threats commonly drive the deterioration of freshwater habitat quality and the loss of hydrological connectivity (Castello & Macedo, 2016; Pelicice et al., 2017). Rivers and lakes, which support high levels of fish biomass, have greater accessibility for human populations compared to terrestrial areas, especially in the neotropics (Antunes et al., 2016; Azevedo-Santos et al., 2019). Larger freshwater species, most of which depend on such fish resources, have low fecundity and slower life history strategies, which makes them particularly vulnerable to aquatic ecosystem declines (He et al., 2020). Combined with increased human pressure on the Amazon's freshwater ecosystems, these characteristics make neotropical freshwater megafauna increasingly threatened (He et al., 2018, 2020).

Semi-aquatic species, which divide their activities between terrestrial and aquatic mediums, have specific habitat requirements due to their unique ecology and behavior. Recent accumulation of fine-scale animal location data has provided unprecedented insights into habitat selection and spatial behavior at levels varying from the resource patch to the landscape scale (Jesmer et al., 2018; Kays et al., 2015; Strandburg-Peshkin et al., 2017). As a result, the understanding of behavioral and environmental factors that drive animal movement decisions in terrestrial and aquatic habitats has increased significantly (Queiroz et al., 2019; Tucker et al., 2018). However, this surge in animal space use research has seldom included detailed studies that combine both riparian and aquatic landscape variables. Studies of semi-aquatic species such as the Eurasian otter (*Lutra lutra*) suggest that space use is driven by river width and less influenced by land-related variables (Weinberger et al., 2016), whereas for smooth-coated otters (*Lontra perspicillata*) rocky bottom and lake depth were important drivers of space use (Anoop & Hussain, 2004). To gain a better understanding of the spatial behavior of semi-aquatic species, it is necessary to draw from advances in animal location tracking and increasingly available high-resolution remote sensing methodology to better qualify their habitat.

Satellite-based multi-spectral remote sensing offers repeatable, standardized, and verifiable spatial information on biodiversity indicators and it is a viable monitoring technique for investigating anthropogenic changes in habitat quality, especially in remote areas (Buma & Lee, 2019; Pettorelli et al., 2014). This methodology is particularly useful for assessing habitat fragmentation

and deforestation, as well as terrestrial and aquatic ecosystem modification (Asner et al., 2013; Broadbent et al., 2008). When combined with on-the-ground observations, remotely sensed satellite data can be a powerful tool to estimate habitat suitability and assess the status of animal populations (Duporge et al., 2020; Palmeirim et al., 2014; Pimm et al., 2015).

Unmanned aerial vehicles (UAVs) are a cost-effective alternative to satellite imagery for the purposes of training and validation of medium spatial resolution-based habitat classification. When equipped with high-resolution digital cameras, UAVs can capture images of sufficient quality to replace on-the-ground verification of land cover (Smith, 2010). UAVs have been successfully used in habitat and wildlife monitoring to identify land cover types and to monitor aquatic and terrestrial wildlife populations (Hodgson et al., 2013), showing potential to increase the efficiency and reduce the cost of on-the-ground surveys and habitat suitability assessments (Chabot & Bird, 2015).

The giant otter (*Pteronura brasiliensis*), the largest freshwater otter, is an aquatic apex predator, present in major freshwater river basins and drainage systems spanning several South American countries, especially Brazil, the Guyanas, Venezuela, Colombia, Bolivia, and Peru (Groenendijk, Duplaix, et al., 2015; Rosas et al., 1999). Giant otters are an endangered (Groenendijk et al., 2021), territorial species, living in social groups of 2–16 individuals, with a dominant reproductive pair. They are almost exclusively piscivorous. Their requirement for both sufficient fish resources and bank habitat with sufficient cover and complexity for denning and resting makes giant otters sensitive to local aquatic habitat loss, bank fragmentation, and degradation (Groenendijk, Hajek, et al., 2015; Palmeirim et al., 2014). Thus, they might play a crucial role as an indicator species of the aquatic ecosystems in which they occur. Nonetheless, there is limited information on the habitat features necessary to maintain stable giant otter populations within and outside protected areas (PAs). Thus, understanding whether giant otter groups favor or avoid certain types of terrestrial and aquatic landscape can contribute toward the preservation of the species and its neotropical freshwater habitat.

We studied giant otter family groups in oxbow lakes of Madre de Dios, a biodiversity hotspot in Peru. Madre de Dios province holds several PAs, where giant otter populations are slowly recovering from severe recent declines caused predominantly by commercial hunting (Groenendijk et al., 2014; Pimenta, Antunes, et al., 2018). However, in recent years the region experienced expansion of artisanal small-scale gold mining (hereafter gold mining), mainly along watersheds outside PAs (Asner et al., 2013; Caballero-Espejo et al., 2018). When

unregulated, ecotourism may also represent a threat to giant otter populations. Our first objective was to examine habitat selection of giant otters, particularly at the scale of patches within oxbow lake group territories (Johnson, 1980). To achieve this goal, we used location data of giant otter groups collected visually within and outside PAs. We combined these data with high-resolution satellite and UAV images to examine relationships between otter presence and structural habitat. We developed variables describing both the aquatic and terrestrial characteristics of oxbow lakes and their banks. We hypothesized that giant otters would forage close to areas with denser forest cover, reflecting their need for intact habitat and suitable resting areas and shelter. Additionally, we hypothesized that giant otters would favor aquatic environments where their probability of finding fish would be increased and their ability to swim and forage would be maximized, to achieve higher fish capture rates and optimal foraging. Our additional goal was to generate maps of giant otter habitat suitability in oxbow lakes throughout Madre de Dios from high-resolution UAV and satellite imagery of oxbow lakes to inform management decisions. We developed suitability maps estimating the probability that giant otters would use open water and bank areas within each oxbow lake, based on the best-supported predictors of giant otter habitat selection.

2 | METHODS

2.1 | Study area

The Madre de Dios province in south-eastern Peru is characterized by tropical forests, floodplains, and wetlands (Hamilton et al., 2007). Madre de Dios presents two distinct seasons in terms of precipitation: wet (January–March) and dry (July–September), and two transitional periods between seasons: wet to dry (April–June) and dry to wet (October–December). This study focuses on oxbow lakes formed by the Madre de Dios and Manu rivers. Oxbow lakes are created when a river meander becomes isolated from the main stream over long periods of time (Terborgh et al., 2018). The territory of a giant otter group in Madre de Dios typically includes one or two oxbow lakes (Groenendijk, Duplaix, et al., 2015). During the dry season, giant otters tend to remain in these oxbow lakes (Groenendijk et al., 2005). Our study included 21 oxbow lakes, eight of which were located inside Manu National Park (MNP; 11°41' S, 71°13' W) and four in the Amarakaeri Communal Reserve (ACR; 12°25' S, 70°42' W; Figure 1). Of these 12 lakes, 5 are subject to continual ecotourism activities. Nine lakes in the lower Madre de Dios river (12°40' S,

69°53' W) are outside PAs and are subject to human activities, such as commercial fishing, gold mining, and occasional ecotourism (Barocas et al., 2021; Mendoza et al., 2017). Gold mining in this area is mostly informal (Cuya et al., 2021; Elmes et al., 2014).

2.2 | Giant otter habitat use data

We surveyed oxbow lakes for giant otters between May 2018 and November 2019 (Table S1). We used Grabner XR Trekking inflatable rubber boats (Grabner®, Vienna, Austria) to navigate the lakes. We visited lakes for two daily sessions based on giant otter activity times and visibility (5:30 a.m. to noon, 2–5 p.m.). Giant otter groups were followed as long as there was visual contact. Observation sessions lasted an average of 64.1 min (\pm SE = 5.7). When a group of giant otters was identified, we followed it in the open water from a distance of 30–100 m, keeping the minimum distance for which there were no evident changes in giant otter behavior as a result of our presence (Bateman & Fleming, 2017). This distance varied between groups studied, as some were more tolerant to human presence. We maintained a consistent distance from the start to the end of each observation session. We registered all significant behavioral events and performed a scan sample every 5 min (Altmann, 1974). We registered behaviors at the group level because it was not possible to follow individual otters, which constantly surface and dive in the murky water. Giant otter observed in the body of water were registered as “swimming” (Barocas et al., 2022).

Each survey team recorded the location of groups every 5 min, using a hand-held Garmin GPS. To record the locations, we estimated the distance and registered the approximate centroid of each giant otter group. In order to reduce observer disturbance, we followed groups at a distance of 30–100 m, following guidelines from Groenendijk et al. (2005). Because visibility limited data collection in terrestrial habitats, we only considered habitat use inside lakes and along banks. Otters foraging and swimming among macrophytes and flooded vegetation were visible and registered. To avoid bias due to occupying the same locations for periods of time (autocorrelation), such as resting sites, we collapsed all points clustered within a 10-m distance from each other in a 1-h time window. We considered each set of collapsed points as a single used location in the final dataset.

2.3 | Habitat mapping from UAV images

We used high-resolution images taken by a UAV to characterize giant otter habitat structure (Strandburg-Peshkin

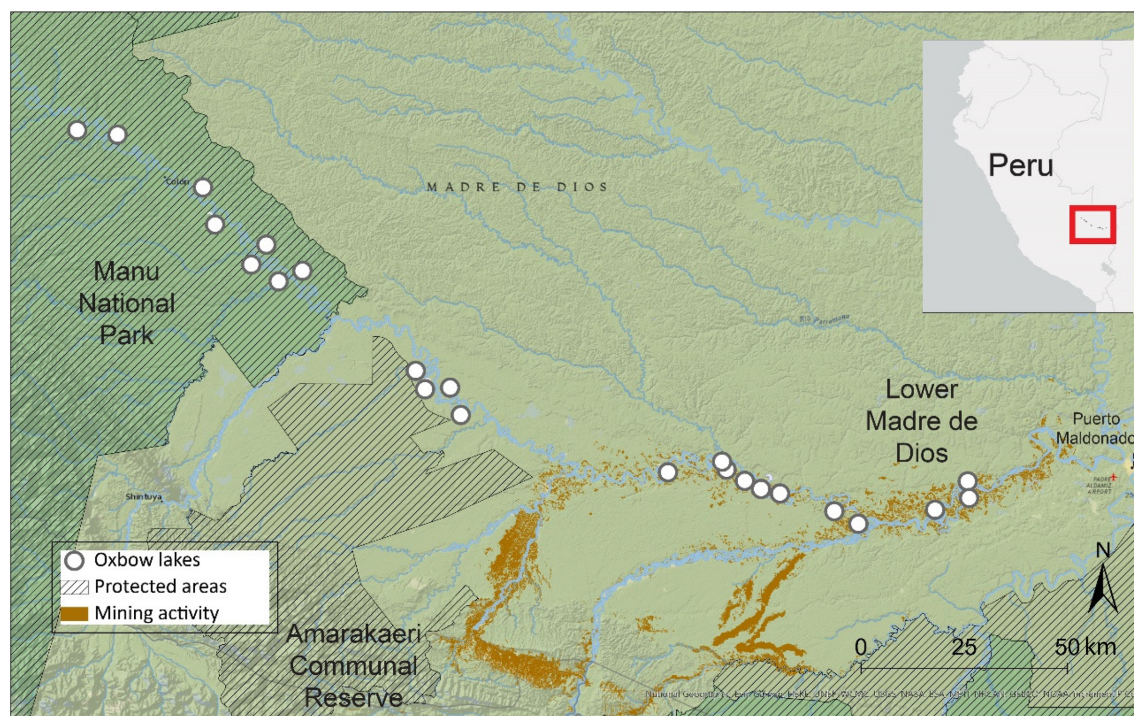


FIGURE 1 Map of giant otter research area showing the oxbow lakes mapped with unmanned aerial vehicles

et al., 2017; Szantoi et al., 2017; Woodget et al., 2017). We used a DJI Mavic PRO quadcopter (DJI Inc., Shenzhen, China), a portable low-cost device with sufficient maneuverability and good resistance to field conditions. The UAV was provided with a camera with a 1/2.3" CMOS (Complementary Metal Oxide Semiconductor) sensor which captures red, green, and blue (RGB) bands of light. We overflew oxbow lakes at 180 m above water's surface, covering the entire area of lakes and a 200-m buffer of terrestrial habitat surrounding lake banks. We used the pix4Dcapture application (Pix4Dcapture 3.2; Pix4D SA, Lausanne, Switzerland) for planning flight missions with a minimum of 80% horizontal and 60% vertical overlap between images. We only flew UAVs when conditions were optimal for image capture (low sunlight, slow winds, and reduced cloud cover). Flight missions were performed on the same day (three to seven missions per lake) over a period of 2 h, to avoid variability in sunlight and shadow.

We used the DroneDeploy online mapping platform to stitch together individual UAV images taken in different lakes and create geometrically correct aerial images. We created drone maps, or orthomosaics, of each lake using UAV images displaying RGB bands (DroneDeploy, 2020). We also created vegetation maps using a VARI index, a measure of the "greenness" in images captured with RGB cameras (Mckinnon & Hoff, 2017). The Visible Atmospherically Resistant Index (VARI) reflects the type of cover in the image: water surface, aquatic vegetation, and forest cover,

and is more sensitive to the vegetation fraction (Gitelson et al., 2002). Additionally, we were able to create digital elevation models (DEMs) by calculating the altitudes of objects in the images using the DroneDeploy tool for digital terrain models. All maps were resampled to a standard resolution of 1 m/pixel (Table 1).

We produced land cover classification (LCC) of lacustrine habitat for the 21 lakes using a supervised classification with the Semi-Automatic Classification Plugin (SCP) for Quantum Geographic Information systems (QGIS) (Congedo, 2016). Selecting areas with similar pixel values (RGB wavelengths, VARI index, and altitude), we created training areas or regions of interest (ROIs) for five different land-cover classes: open water, free-floating vegetation (floating macrophytes), flooded vegetation (shrubs, palms, and fig trees), forest canopy, and barren soil (Table 1; Figure 2). We used ROIs based on VARI index, the DEM and each of the three RGB wavelength layers, to train the Spectral Angle Mapping Algorithm of the SCP and assign a class value to all pixels. Processing required the creation of approximately 200 ROIs per lake. We obtained 21 raster layers corresponding to each lake with pixel values of 0, for unclassified cells, and values from 1 to 5 corresponding to each land cover class.

Oxbow lake banks are covered by different types of forest which have specific features such as plant community and flooding regimes (Salo et al., 1986). Thus, to characterize lake bank vegetation, we used five additional variables describing vegetation types from a floodplain

TABLE 1 Description, codes, and sources of variables used as predictors for giant otter habitat selection modeling in Madre de Dios, Peru, 2018–2019

Covariate	Code	Description	Source
Topography			
Compound topographic index	cti	High values in areas with poor drainage and tendency for flooding	USGS (Danielson & Gesch, 2011)
Distance			
Distance to river	dist_riv	Distance from nearest point on river	Sentinel-2 image (Drusch, 2012)
Distance to lake edge	dist_edge	Distance from digitized lake edge	Sentinel-2 image (Drusch, 2012)
Distance to human population	dist_hum	Distance from habitation center	WorldPop, 2018
Land cover			
Barren soil	dlc_bs	Exposed soil or sand	UAV images
Flooded vegetation	dlc_bv	Vegetation over standing water	UAV images
Forest canopy cover	dlc_fc	Area covered by the forest canopy	UAV images
Floating vegetation	dlc_fm	Free floating macrophytes on body of water	UAV images
Water surface	dlc_wa	Surface of water body	UAV images
Fallen tree area	ft_area	Logs over water where otters often rest	UAV images
Geomorphology			
Meander belt late successional forest	ham_mbf	Diverse, late successional broadleaf forest; largely closed canopy	Hamilton et al. (2007)
Meander belt early successional forest	ham_mbs	Herbaceous vegetation or, most often, either stands of <i>Tessaria</i> or <i>Cecropia</i> with <i>Gynerium</i> understory	Hamilton et al. (2007)
Palm swamp	swamp	Often dominated by the palm <i>Mauritia flexuosa</i> and figs; not flooded in the dry season	Hamilton et al. (2007)
Backswamp forest	ham_bsf	Similar to palm swamp with standing water	Hamilton et al. (2007)
Terra firme	ham_fir	Rainforest not inundated by floods	Hamilton et al. (2007)

classification of the entire Madre de Dios basin, developed from satellite images by Hamilton et al. (2007) (Table 1). Each variable represents a type of vegetation with its associated soil properties, including early and late succession meander belts, palm swamps, and terra firme.

2.4 | Additional habitat variables

We searched the literature for landscape characteristics that could directly or indirectly influence giant otter habitat suitability (Groenendijk, Hajek, et al., 2015; Lima et al., 2012; Pimenta, Gonçalves, et al., 2018) and developed a set of 15 variables that correspond to structural, environmental, and anthropogenic components of the landscape. UAV LCC represented areas inside and in the immediate surroundings of lakes. Each class was transformed into a separate binary raster layer. Additionally, using the UAV orthomosaics, we developed a variable reflecting circular areas inside lakes containing fallen

trees. Fallen tree areas were also transformed to binary raster layers. Otters tend to return to these logs for resting (Rosas et al., 2015), thus not accounting for the influence of such sites may bias the analysis (Manly et al., 2002).

We used a DEM (Rabus et al., 2003) of the area to obtain a compound topographic index (CTI) using the Geomorphometry and Gradient Metrics toolbox (Evans et al., 2014) for ArcGIS 10.5 (ESRI, 2016). CTI, or “soil wetness,” presents high values in areas with poor drainage and tendency for flooding like lakes, rivers, creeks, and swamps, and can be used to inspect aspects of hydrologic systems (Moore et al., 1991). Drainage and flooding influence soil type, siltation, and water clarity which can vary in different areas of the lakes (Table 1).

We additionally created raster layers representing distances to river, lake boundary, and human population. We used the SCP plugin (Congedo, 2016) to identify areas covered by water from Sentinel-2 satellite images (Drusch, 2012) and classified them as river. To create lake bank polygons, we manually digitized lake edges with UAV orthomosaics as reference. We also obtained human

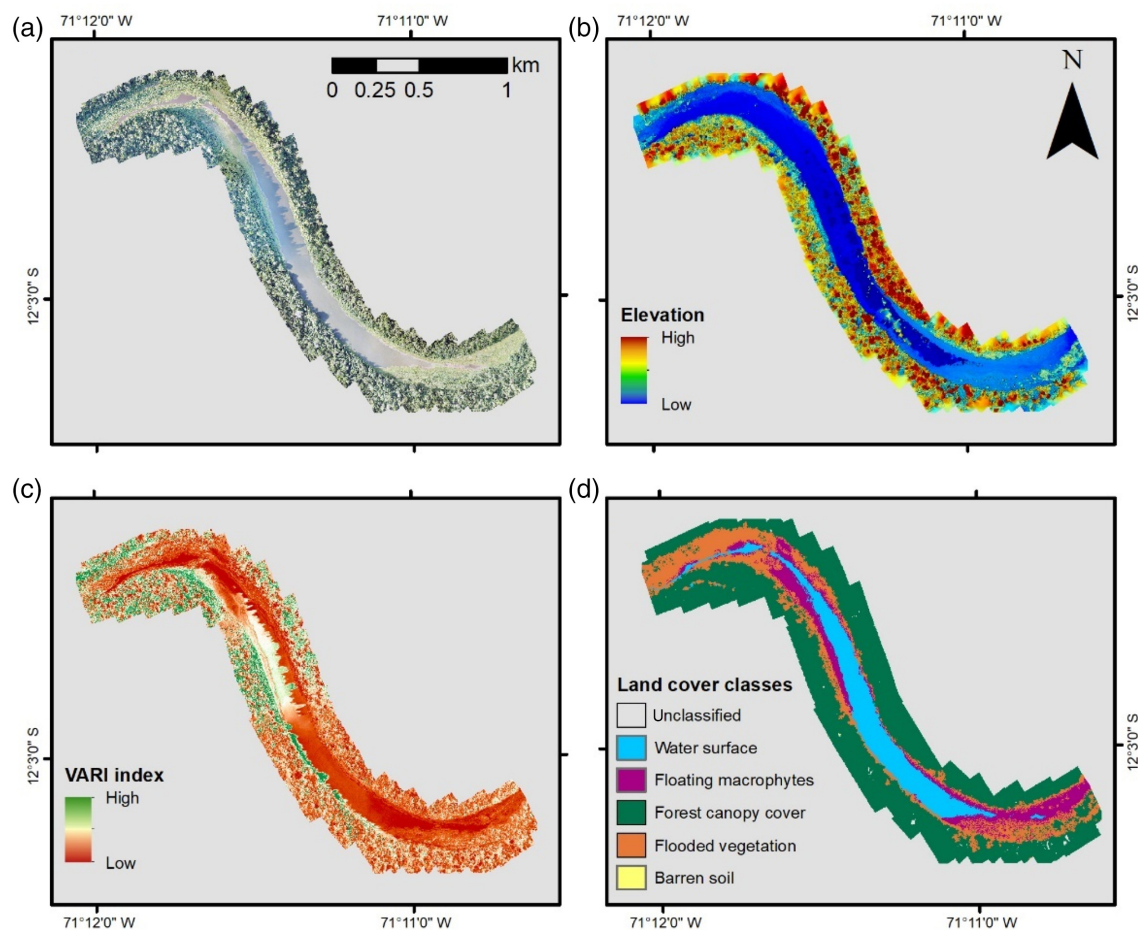


FIGURE 2 Processing of unmanned aerial vehicle (UAV) image to derive habitat suitability illustrated for Otorongo oxbow lake. Images from the UAV are integrated into a high-resolution orthomosaic (a). Color pixels are processed into an elevation layer (b) and each pixel's greenness is also modeled as a VARI index (c). Semi-automatic supervised classification is used for derivation of land-cover classes (d).

population information in Madre de Dios from a population count dataset of Peru for the year 2018 (WorldPop, 2018). We produced raster layers of distances to rivers, lake edge, and human population (Table 1), using the Euclidean Distance tool from ArcGIS 10.5 (ESRI, 2016).

2.5 | Data analysis

We implemented a multi-scale approach to assess the most appropriate response scale for analysis of habitat variables (Macdonald et al., 2019; Pimenta, Gonçalves, et al., 2018), subsequently specified as predictors in a resource selection function (RSF; Manly et al., 2002) which examined used and available habitat for giant otters within oxbow lakes. All areas inside lakes were considered available habitat for giant otters, because they constitute part of group territories (Groenendijk, Duplaix, et al., 2015). For each lake, we generated pseudo-absence points in equal number to otter presence locations. To

ensure sufficient sampling, for lakes with fewer used locations, we generated 100 pseudo-absence points. We assessed each variable at eight different spatial scales, by using different radii of circular buffers at 25, 50, 75, 100, 125, 150, 175, and 200 m around each used and available location, and assigning to each point the average value of the cells within the buffers. First, to exclude poorly represented habitat features, we removed variables represented in less than 10% of locations. Second, to assess the optimal scale we applied univariate generalized linear mixed models (GLMMs; Harrison et al., 2018) with each variable specified as a fixed effect and lake identity as a random effect. The response variable was specified as an observed location (1) or an available point (0). We removed variables showing explanatory power in the univariate GLMM at $p > .05$. For the remaining variables, we then selected the optimal scale, based on Akaike's information criterion (AIC; Burnham & Anderson, 2002).

We assessed multicollinearity among scale-optimized variables using Pearson's correlation index and variance inflation factors (VIF). We used the *dredge* function to

compare all possible combinations of variables and select the best-supported model using AIC. Coefficients from the best-supported models, all within 2 AIC units, were averaged. To examine the performance of UAV-derived covariates versus covariates developed from satellite images, we also examined two specific models: one with all variables selected developed from UAV images and one with all variables developed from satellite images. To validate our best-supported RSF model, we performed k -folds cross-validation for RSFs with five bins taken from the complete point dataset (Boyce et al., 2002; Houle et al., 2010).

2.6 | Habitat suitability maps

We derived predictions of habitat suitability for each pixel in each lake from the best-supported GLMM. Based on the values of the eight raster layers included in the best-supported model in each pixel, and the matching variable coefficients, we created a layer reflecting the predicted probability giant otters would be found in this pixel. The subsequent maps indicated, based on water vegetation, bank land cover, and canopy structure, which areas in each lake's body of water were most suitable for giant otters. All analyses were performed in R (version 3.1.0; R Development Core Team, 2011), using packages *lme4* (Bates et al., 2014), *MuMin* (Barton & Barton, 2015), and *performance* (Lüdtke et al., 2020).

3 | RESULTS

We observed giant otter groups in 13 of 21 lakes surveyed, 10 inside PAs and 3 in the unprotected lower Madre de Dios (Table S1). We recorded a total of 2955 giant otter locations. Our final dataset included 1561 (84%) locations from PAs and 288 (16%) from the lower Madre de Dios, from 13 family groups (Table S1).

3.1 | Habitat variable selection

Lake bank vegetation types corresponding to terra-firme forest and swamp were discarded due to the lack of representation in areas surrounding lakes for all eight scales assessed. Distance to human habitation, distance to lake edge, and distance to river variables were also excluded from the multivariate model because they showed low explanatory power in the univariate GLMM (p -value > .05) at all assessed scales. Habitat selection by giant otters was best supported at smaller scales for most variables. Water surface, flooded vegetation, forest canopy, and late

TABLE 2 Structure, likelihood, and relative support of six generalized linear mixed models describing giant otter habitat selection in oxbow lakes

Model number	cti 75 m	dlc_bs 50 m	dlc_bv 50 m	dlc_fc 25 m	dlc_fm 25 m	dlc_wa 25 m	ft_area 175 m	ham_bsf 100 m	ham_mbf 25 m	ham_mbs 100	df	logLik	AIC	ΔAIC	Weight
1006	+		+	+		+	+	+	+	+	10	-2574.2	5168.5	0	0.441
1022	+		+		+	+	+	+	+	+	11	-2574.0	5170	1.5	0.208
1008	+		+	+		+	+	+	+	+	11	-2574.1	5170.3	1.82	0.178
942	+	+	+	+		+		+	+	+	9	-2576.1	5170.3	1.87	0.173
UAV			+	+	+	+	+				8	-2590.7	5197.4	28.9	0
Satellite	+							+	+	+	6	-2746.3	5504.6	336.1	0

Note: Data includes giant otter locations in 13 oxbow lakes of Madre de Dios province, Peru, collected during 2018 and 2019.

succession variables performed better at the smallest scales (25 m), whereas the optimal scale for bare soil and flooded vegetation variables was 50 m. The CTI variable influenced habitat selection at a 75-m scale. The early successional forest and backswamp forest variables performed better at a scale size of 100 m. The largest scale size (175 m) was selected for the fallen tree area variable (Tables S2–S11).

3.2 | Model selection

Of the 10 retained variables, no pair of variables showed high collinearity ($|r| > 0.7$; Table S12). From 1024 competing models describing giant otter habitat selection in oxbow lakes, 4 had ΔAICc values lower than 2 (Table 2). The best-supported model included eight variables (AIC weight = 0.41; $R^2_{\text{cond.}} = 0.27$; Figure 3). The strongest predictor was water surface ($\beta \pm \text{SE} = 0.15 \pm 0.04$; Table S13). Giant otter locations were also positively associated with forest canopy ($\beta \pm \text{SE} = 0.15 \pm 0.04$), indicating selection for areas inside lakes in proximity to tree canopy, and negatively associated with flooded vegetation inside lakes ($\beta \pm \text{SE} = -0.46 \pm 0.04$). Otters also selected areas of lakes with low 75-m radius CTI values ($\beta \pm \text{SE} = -0.16 \pm 0.06$). Avoidance of high CTI implies preference for well-drained, less flood-prone bank portions. Cross-validation results indicated good predictive ability of the best-supported model (mean $r \pm \text{SE} = 0.78 \pm 0.09$). The model with only UAV-derived covariates strongly outperformed the model with variables developed from satellite images (UAV AIC = 5197.4, $R^2_{\text{cond.}} = 0.25$; satellite AIC = 5504.6, $R^2_{\text{cond.}} = 0.14$; Table S13), indicating improved ability to predict giant otter habitat selection.

3.3 | Habitat suitability maps

We included giant otter observations for 13 oxbow lakes, spanning a total of 823 hectares, and based on these derived predictions for all 21 oxbow lakes, an area of 1225 ha. Model-based predictions suggested that areas within oxbow lakes varied considerably in habitat suitability (Figures S1–S4). MNP oxbow lakes had similar suitability to lower Madre de Dios lakes subject to human activity (Manu NP – median = 0.54, mean $\pm \text{SE} = 0.47 \pm 0.0002$; lower MdD – median = 0.52, mean $\pm \text{SE} = 0.45 \pm 0.0001$), whereas ACR oxbow lakes scored considerably lower (median = 0.32, mean $\pm \text{SE} = 0.36 \pm 0.0003$; Figure 4), suggesting that gold mining activity did not significantly affect oxbow lake habitat suitability for giant otters. Suitability maps for all three regions

indicated that peripheral areas in lake edges and areas nearer lake banks are less suitable compared to middle and open water areas (Figure 5; Figures S2–S4).

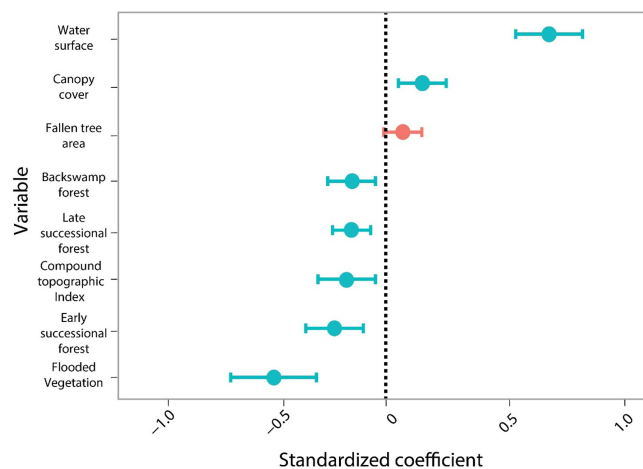


FIGURE 3 Model-averaged selection coefficients of the best-supported model describing giant otter resource selection in 13 oxbow lakes in Madre de Dios province, Peru. Bars represent 95% confidence intervals based on standard errors.

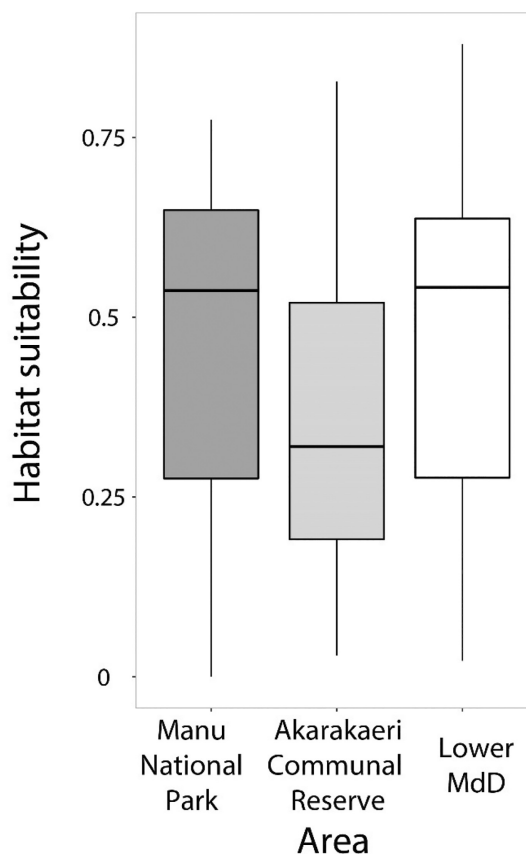


FIGURE 4 Box plots of habitat suitability values for oxbow lakes in three different areas. Predictions were based on the best-supported model describing giant otter resource selection in Madre de Dios province, Peru. Middle lines represent median values.

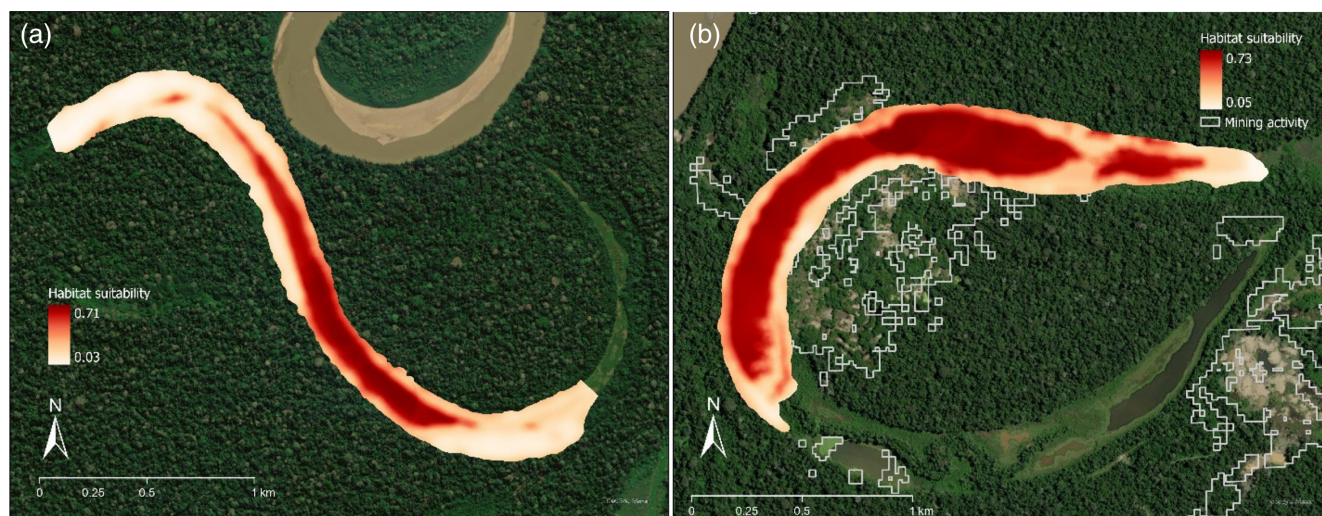


FIGURE 5 Giant otter habitat suitability maps of oxbow lakes in Manu National Park (a) and the lower Madre de Dios, where gold mining activity takes place (b). Habitat suitability was calculated from spatial variables using predictions of the best-supported model based on giant otter family group observations. The background satellite image was provided by ESRI.

4 | DISCUSSION

The terrestrial and aquatic landscape factors that influence habitat selection of semi-aquatic animals at the water-land interface are not well understood. Our analyses, combining high-resolution UAV data and satellite images, demonstrate that giant otters respond to landscape features at scales varying from very local (25 m) up to 200 m. Further, our findings indicate that terrestrial bank landscape characteristics, including forest cover and shelter on lake banks and aquatic factors such as obstacles and resting logs in the water body are both significant determinants of giant otter habitat use. UAV-derived variables showed stronger performance compared to variables developed from satellite images.

4.1 | Giant otter habitat selection

From the perspective of piscivorous semi-aquatic species, freshwater landscapes can be heterogeneous in foraging conditions. Our results suggest preference of giant otters for open water and avoidance of floating vegetation, which may reflect selection of areas within lakes that maximize foraging yield. Giant otters primarily rely on fish (Rosas et al., 1999) and thus should favor conditions that enable them to freely swim and forage. While swimming and diving, giant otters may get entangled in or blocked by water plants, which could reduce their efficiency in detecting and capturing fish. This could explain avoidance of such features (Groenendijk, 2019). Otters should also favor areas with increased bottom complexity, which would maximize fish occurrence (Mol &

Ouboter, 2004). Detailed mapping of oxbow lake bottom bathymetry and hotspots of fish distribution within lakes may improve the ability to predict aquatic areas more likely to be used by giant otters.

Giant otters were found in areas near logs that project above the water's surface, which they are known to use for rest and social activity (Rosas et al., 2015). Additional benefits of basking and sun exposure for other species include thermoregulation (Brown & Downs, 2007; Matthews et al., 2017) and parasite avoidance (Bush & Clayton, 2018). Resting above water level may also provide protection from predators found in the area's oxbow lakes, such as black caiman (*Melanosuchus niger*) and jaguar (*Panthera onca*). In oxbow lakes, where bank areas are mostly covered by vegetation, locations near water that enable giant otter an enhanced field of vision and exposure to the sun are a limited resource and thus may be particularly valuable.

Terrestrial features selected by giant otters included dense vegetation and soil which is less prone to flooding. Degraded and fragmented forest may drive deterioration of the aquatic habitat (Castello & Macedo, 2016) and a decline in fish resources (Brejao et al., 2017). In addition, better bank forest cover and less flood-prone soil could provide higher quality sites for signaling, resting, and denning (Lima et al., 2012). Because giant otters also use dens and latrines for chemical communication and territory demarcation (Leuchtenberger & Mourão, 2009), it may be beneficial to select locations with minimal exposure to the elements, where odorous messages can remain for longer periods (Alberts, 1992; Nie et al., 2012). These factors may explain the preference for foraging areas near better forest cover. Our findings also suggest

that giant otters avoid areas near banks that are flooded during the wet season. As both satellite and UAV data were used to develop layers (Hamilton et al., 2007) and the majority of giant otter data were collected during the dry season, this may reflect selection for bank areas less likely to be flooded. Our findings illustrate how satellite-derived images and UAV data can be combined to gain a better understanding of habitat complexity. Seasonal variation in giant otter habitat use was observed in riverine systems and is presumed to be driven by fish availability and movement of larger fish shoals, on which giant otter groups rely (Leuchtenberger et al., 2013). Understanding whether giant otter territories similarly vary in the wet season in oxbow lakes should be a promising research direction.

4.2 | Advantages of UAV images

Our findings suggest that land cover and DEM variables collected by UAV are more predictive than variables derived from satellite images. Studies in other aquatic systems have shown that the combination of both data sources provides a more complete assessment of local habitat quality and thus should be favored (Gray et al., 2018; Ruwaimana et al., 2018). Although many satellite products are freely available, a significant proportion of products are not, and their analysis may require a large investment in man hours and processing power. Some satellite products can provide resolution comparable to the one obtained by UAVs (Pettorelli et al., 2014). In our system, the resources applied in the collection and processing of UAV imagery were considerable (including drone and battery purchase, energy provision in the field, 2–8 h of flights in each oxbow lake, and considerable processing time for UAV images), but not prohibitive (Table S14). Given that giant otters are semi-aquatic and their space use is determined not only by water-related variables but also by features in the bank landscape, UAV methodology could be promising for studying oxbow lake and floodplain systems. In such settings, human activity, which drives significant deterioration of giant otter bank habitat (Palmeirim et al., 2014), may have increased influence.

Driven by recent increases in gold mining, deforestation has transformed several aquatic habitats in the Amazon and specifically in Madre de Dios (Asner & Tupayachi, 2017; Caballero-Espejo et al., 2018). In the area's unprotected oxbow lakes, vegetation surrounding water has decreased by up to 50% (Caballero-Espejo et al., 2018; Table S1). The majority of our observations were obtained in protected oxbow lakes, which have a relatively intact canopy. This unbalanced representation may explain findings suggesting that habitat suitability

does not decrease in unprotected oxbow lakes. Nonetheless, the observed preference of giant otters for higher proportions of bank canopy cover suggests that increased gold mining and additional human activities in lake banks may have implications for giant otter space use and distribution. In addition, depleted fish assemblages in unprotected oxbow lakes (Barocas et al., 2021) may make them suboptimal habitats, an important reminder that studies of habitat suitability cannot rely solely on images “from the sky,” and that intensive on-ground sampling can reveal subtle but important components of habitat suitability.

4.3 | Conservation implications

Our model predictions provided suitability maps for oxbow lakes in Madre de Dios, indicating areas in the water body that are more likely to be used by giant otters. Several surveyed lakes are used as ecotourism destinations, where giant otters are one of the main attractions (Barocas et al., 2022; Staib & Schenck, 1994). Thus, knowledge of probable space-use patterns of giant otters can be used to guide tour operators and managing authorities on the choice of viewing areas and for the designation of no-entry areas within oxbow lakes, which should enable giant otter groups to forage without the pressure of human activity. Ecotourism is an important source of revenue for local communities in the Peruvian Amazon, and provides alternative livelihoods that—if responsibly implemented—can have fewer impacts on giant otters, other aquatic wildlife, and freshwater ecosystem services (Kirkby et al., 2010). Our data can help make these ecotourism initiatives more profitable and more sustainable, an endeavor that will require financial benefits to accrue to local stakeholders that are engaged in the process (Stronza & Pêgas, 2008). In Peru and elsewhere, especially in PAs, the use of UAVs to assess freshwater habitat quality needs to be approved by local authorities.

In addition, analyzed on a larger scale, our findings should help managers identify aquatic areas with greater giant otter suitability, guiding prioritization efforts for conservation. Our results provide a detailed, much-needed assessment of giant otter habitat preferences which can also guide restoration efforts for the species throughout its range. Previous authors emphasize how increased freshwater connectivity and well-drained bank areas constitute favorable giant otter habitat (Pimenta, Gonçalves, et al., 2018). Our results further support this but also stress the importance of avoiding deforestation, protecting pristine, well-drained riparian areas, and prioritizing the maintenance of open freshwater zones. Finally, previous work also demonstrates that in addition to the integrity of the terrestrial and aquatic portions of

giant otter freshwater habitat, a sufficient fish biomass is necessary (Palmeirim et al., 2014).

Our examination of aquatic ecosystem quality, combining UAV and satellite-derived variables, indicates that giant otters favor open water areas free of macrophytes and well-drained bank areas with more vegetation cover. Used within a multi-scale framework, UAV imaging-derived habitat modeling can be a promising conservation tool for this habitat system, allowing detailed assessment of both aquatic and terrestrial habitat quality. Conserving tropical floodplains inhabited by similar aquatic megafauna could be achieved by minimizing deforestation, and promoting sustainable fish extraction and ecotourism, particularly in areas surrounding lake and riverbanks.

AUTHOR CONTRIBUTIONS

Jessica Groenendijk, David W. Macdonald, Ronald R. Swaisgood, and Adi Barocas designed the research. Nicole Abanto Valladares, Alejandro Alarcon Pardo, and Adi Barocas collected UAV and giant otter location data. Nicole Abanto Valladares and Adi Barocas analyzed the data. Luca Chiaverini and Lauren A. Harrington assisted with data analysis and manuscript writing. Nicole Abanto Valladares and Adi Barocas wrote the manuscript. All authors contributed critically to manuscript writing and approved it for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Giant otter location data will be provided by the corresponding author upon request.

ORCID

Lauren A. Harrington  <https://orcid.org/0000-0002-7212-2336>

Adi Barocas  <https://orcid.org/0000-0001-5435-9711>

REFERENCES

- Alberts, A. C. (1992). Constraints on the design of chemical communication systems in terrestrial vertebrates. *The American Naturalist*, 139, S62–S89.
- Altmann, J. (1974). Observational study of behavior: Sampling methods. *Behaviour*, 49, 227–266.
- Anoop, K. R., & Hussain, S. A. (2004). Factors affecting habitat selection by smooth-coated otters (*Lutra perspicillata*) in Kerala, India. *Journal of Zoology*, 263, 417–423.
- Antunes, A. P., Fewster, R. M., Venticinque, E. M., Peres, C. A., Levi, T., Rohe, F., & Shepard, G. H. (2016). Empty forest or empty rivers? A century of commercial hunting in Amazonia. *Science Advances*, 2, e1600936. <https://doi.org/10.1126/sciadv.1600936>
- Asner, G. P., Llactayo, W., Tupayachi, R., & Luna, E. R. (2013). Elevated rates of gold mining in the Amazon revealed through high-resolution monitoring. *Proceedings of the National Academy of Sciences of the United States of America*, 110, 18454–18459.
- Asner, G. P., & Tupayachi, R. (2017). Accelerated losses of protected forests from gold mining in the Peruvian Amazon. *Environmental Research Letters*, 12, 1–8.
- Azevedo-Santos, V. M., Frederico, R. G., Fagundes, C. K., Pompeu, P. S., Pelicice, F. M., Padial, A. A., Nogueira, M. G., Fearnside, P. M., Lima, L. B., Daga, V. S., Oliveira, F. J. M., Vitule, J. R. S., Callisto, M., Agostinho, A. A., Esteves, F. A., Lima-Junior, D. P., Magalhães, A. L. B., Sabino, J., Mormul, R. P., ... Henry, R. (2019). Protected areas: A focus on Brazilian freshwater biodiversity. *Diversity and Distributions*, 25, 442–448.
- Barocas, A., Araújo Flores, J. M., Alarcon Pardo, A., Macdonald, D. W., & Swaisgood, R. R. (2021). Reduced dry season fish biomass and depleted carnivorous fish assemblages in unprotected tropical oxbow lakes. *Biological Conservation*, 257, 109090.
- Barocas, A., Farfan, J., Groenendijk, J., Mendoza, J., Silva, J., Mujica, O., Ochoa, J. A., Macdonald, D. W., & Swaisgood, R. R. (2022). Disturbance-specific behavioral responses of giant otters exposed to ecotourism and extractive activities. *Animal Conservation*, 25, 15–26.
- Barton, K., & Barton, M. K. (2015). Package 'mumin.' Version 1:18.
- Bateman, P. W., & Fleming, P. A. (2017). Are negative effects of tourist activities on wildlife over-reported? A review of assessment methods and empirical results. *Biological Conservation*, 211, 10–19. <https://doi.org/10.1016/j.biocon.2017.05.003>
- Bates, D. M., Maechler, M., Bolker, B. M., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. <http://arxiv.org/abs/1406.5823>
- Boyce, M. S., Vernier, P. R., Nielsen, S. E., & Schmiegelow, F. K. A. (2002). Evaluating resource selection functions. *Ecological Modelling*, 157, 281–300.
- Brejao, G. L., Hoesinghaus, D. J., Ferraz, S. F. B., & Casatti, L. (2017). Threshold responses of Amazonian stream fishes to timing and extent of deforestation. *Conservation Biology*, 32, 860–871.
- Broadbent, E. N., Asner, G. P., Keller, M., Knapp, D. E., Oliveira, P. J. C., & Silva, J. N. (2008). Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon. *Biological conservation*, 141, 1745–1757.

- Brown, K. J., & Downs, C. T. (2007). Basking behaviour in the rock hyrax (*Procapra capensis*) during winter. *African Zoology*, 42, 70–79.
- Buma, W. G., & Lee, S.-I. (2019). Multispectral image-based estimation of drought patterns and intensity around Lake Chad, Africa. *Remote Sensing*, 11, 2534.
- Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference* (2nd ed.). Springer.
- Bush, S. E., & Clayton, D. H. (2018). Anti-parasite behaviour of birds. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373, 20170196.
- Caballero-Espejo, J., Messinger, M., Román-Dañobeytia, F., Ascorra, C., Fernandez, L. E., & Silman, M. (2018). Deforestation and forest degradation due to gold mining in the Peruvian Amazon: A 34-year perspective. *Remote Sensing*, 10, 1–17.
- Carpenter, S. R., Stanley, E. H., & Vander Zanden, M. J. (2011). State of the world's freshwater ecosystems: Physical, chemical, and biological changes. *Annual Review of Environment and Resources*, 36, 75–99.
- Castello, L., & Macedo, M. N. (2016). Large-scale degradation of Amazonian freshwater ecosystems. *Global Change Biology*, 22, 990–1007.
- Chabot, D., & Bird, D. M. (2015). Wildlife research and management methods in the 21st century: Where do unmanned aircraft fit in? *Journal of Unmanned Vehicle Systems*, 3, 137–155.
- Congedo, L. (2016). Semi-Automatic Classification Plugin Documentation. Release 6.0.1.1.
- Cuya, A., Glikman, J. A., Groenendijk, J., Macdonald, D. W., Swaisgood, R. R., & Barocas, A. (2021). Socio-environmental perceptions and barriers to conservation engagement among artisanal small-scale gold mining communities in southeastern Peru. *Global Ecology and Conservation*, 31, e01816.
- Danielson, J. J., & Gesch, D. B. (2011). *Global multi-resolution terrain elevation data 2010 (GMTED2010)*. US Department of the Interior, US Geological Survey.
- DroneDeploy. (2020). DroneDeploy's ultimate drone glossary. An A-Z guide for drone professionals and enthusiasts.
- Drusch, M., Umberto, D. B., Sébastien, C., Olivier, C., Veronica, F., Ferran, G., Bianca, H., et al. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote sensing of Environment*, 120, 25–36.
- Duporge, I., Isupova, O., Reece, S., Macdonald, D. W., & Wang, T. (2020). Using very-high-resolution satellite imagery and deep learning to detect and count African elephants in heterogeneous landscapes. *Remote Sensing in Ecology and Conservation*, 7, 369–381.
- Elmes, A., Ipanaque, J. G. Y., Rogan, J., Cuba, N., & Bebbington, A. (2014). Mapping licit and illicit mining activity in the Madre de Dios region of Peru. *Remote Sensing Letters*, 5, 882–891.
- ESRI. (2016). ArcGIS 10.5. ESRI.
- Evans, J. S., Oakleaf, J., Cushman, S. A., & Theobald, D. (2014). An ArcGIS toolbox for surface gradient and geomorphometric modeling (v2.0-0).
- Gitelson, A. A., Kaufman, Y. J., Stark, R., & Rundquist, D. (2002). Novel algorithms for remote estimation of vegetation fraction. *Remote sensing of Environment*, 80, 76–87.
- Gray, P. C., Ridge, J. T., Poulin, S. K., Seymour, A. C., Schwantes, A. M., Swenson, J. J., & Johnston, D. W. (2018). Integrating drone imagery into high resolution satellite remote sensing assessments of estuarine environments. *Remote Sensing*, 10, 1257.
- Groenendijk, J. (2019). *The giant otter: Giants of the Amazon*. Pen and Sword.
- Groenendijk, J., Duplaix, N., Marmontel, M., Van Damme, P., & Schenck, C. (2015). *Pteronura brasiliensis*, giant otter. The IUCN Red List of Threatened Species 2015: e.T1711A21938411.
- Groenendijk, J., Duplaix, N., Marmontel, M., Van Damme, P., & Schenck, C. (2021). *Pteronura brasiliensis*. The IUCN Red List of Threatened Species 2015: e.T18711A21938411.
- Groenendijk, J., Hajek, F., Duplaix, N., Reuther, C., Van Damme, P., & Schenck, C. (2005). Surveying and monitoring distribution and population trends of the giant otter (*Pteronura brasiliensis*). Habitat.
- Groenendijk, J., Hajek, F., Johnson, P. J., Macdonald, D. W., Calvimontes, J., Staib, E., & Schenck, C. (2014). Demography of the giant otter (*Pteronura brasiliensis*) in Manu National Park, south-eastern Peru: Implications for conservation. *PLoS One*, 9, e106202.
- Groenendijk, J., Hajek, F., Schenck, C., Staib, E., Johnson, P. J., & Macdonald, D. W. (2015). Effects of territory size on the reproductive success and social system of the giant otter, south-eastern Peru. *Journal of Zoology*, 296, 153–160.
- Hamilton, S. K., Kellndorfer, J., Lehner, B., & Tobler, M. (2007). Remote sensing of floodplain geomorphology as a surrogate for biodiversity in a tropical river system (Madre de Dios, Peru). *Geomorphology*, 89, 23–38.
- Harrison, X. A., Donaldson, L., Correa-Cano, M. E., Evans, J., Fisher, D. N., Goodwin, C. E. D., Robinson, B. S., Hodgson, D. J., & Inger, R. (2018). A brief introduction to mixed effects modelling and multi-model inference in ecology. *PeerJ*, 2018, 1–32.
- He, F., Bremerich, V., Zarfl, C., Geldmann, J., Langhans, S. D., David, J. N. W., Darwall, W., Tockner, K., & Jähnig, S. C. (2018). Freshwater megafauna diversity: Patterns, status and threats. *Diversity and Distributions*, 24, 1395–1404.
- He, F., Langhans, S. D., Zarfl, C., Wanke, R., Tockner, K., & Jähnig, S. C. (2020). Combined effects of life-history traits and human impact on extinction risk of freshwater megafauna. *Conservation Biology*, 35, 643–653.
- Hodgson, A., Kelly, N., & Peel, D. (2013). Unmanned aerial vehicles (UAVs) for surveying marine fauna: A dugong case study. *PLoS One*, 8, e79556.
- Houle, M., Fortin, D., Dussault, C., Courtois, R., & Ouellet, J. P. (2010). Cumulative effects of forestry on habitat use by gray wolf (*Canis lupus*) in the boreal forest. *Landscape Ecology*, 25, 419–433.
- Jesmer, B. R., Merkle, J. A., Goheen, J. R., Aikens, E. O., Beck, J. L., Courtemanch, A. B., Hurley, M. A., McWhirter, D. E., Miyasaki, H. M., Monteith, K. L., & Kauffman, M. J. (2018). Is ungulate migration culturally transmitted? Evidence of social learning from translocated animals. *Science*, 361, 1023–1025.
- Johnson, D. H. (1980). The comparison of usage and availability measurements for evaluating resource preference. *Ecology*, 61, 65–71.
- Kays, R., Crofoot, M. C., Jetz, W., & Wikelski, M. (2015). Terrestrial animal tracking as an eye on life and planet. *Science*, 348, 2478.
- Kirkby, C. A., Giudice-Granados, R., Day, B., Turner, K., Velarde-Andrade, L. M., Dueñas-Dueñas, A., Lara-

- Rivas, J. C., & Yu, D. W. (2010). The market triumph of ecotourism: An economic investigation of the private and social benefits of competing land uses in the Peruvian Amazon. *PLoS One*, 5, e13015.
- Leuchtenberger, C., & Mourão, G. (2009). Scent-marking of giant otter in the southern Pantanal, Brazil. *Ethology*, 115, 210–216. <https://doi.org/10.1111/j.1439-0310.2008.01607.x>
- Leuchtenberger, C., Oliveira-Santos, L. G. R., Magnusson, W., & Mourão, G. (2013). Space use by giant otter groups in the Brazilian Pantanal. *Journal of Mammalogy*, 94, 320–330.
- Lima, D. S., Marmontel, M., & Bernard, E. (2012). Site and refuge use by giant river otters (*Pteronura brasiliensis*) in the Western Brazilian Amazonia. *Journal of Natural History*, 46, 729–739.
- Lüdecke, D., Makowski, D., Waggoner, P., & Patil, I. (2020). Package ‘performance’.
- Macdonald, D. W., Bothwell, H. M., Kaszta, Z., Ash, E., Bolongon, G., Burnham, D., Can, Ö. E., Campos-Arceiz, A., Channa, P., Clements, G. R., Hearn, A. J., Hedges, L., Htun, S., Kamler, J. F., Kawanishi, K., Macdonald, E. A., Mohamad, S. W., Moore, J., Naing, H., ... Cushman, S. A. (2019). Multi-scale habitat modelling identifies spatial conservation priorities for mainland clouded leopards (*Neofelis nebulosa*). *Diversity and Distributions*, 25, 1639–1654.
- Manly, B. F. J., McDonald, L. L., Thomas, D. L., McDonald, T. L., & Erickson, W. P. (2002). *Resource selection by animals. Statistical design and analysis for field studies* (2nd ed.). Kluwer Academic Publishers.
- Matthews, J. K., Stawski, C., Körtner, G., Parker, C. A., & Geiser, F. (2017). Torpor and basking after a severe wildfire: Mammalian survival strategies in a scorched landscape. *Journal of Comparative Physiology B*, 187, 385–393.
- Mckinnon, T., & Hoff, P. (2017). Comparing RGB-based vegetation indices with NDVI for drone based agricultural sensing.
- Mendoza, J. A., Huamani, K., Sebastian, G., & Ochoa, J. A. (2017). Giant otter (*Pteronura brasiliensis*) distribution and population status in Madre de Dios River basin, southeastern Peru. *Revista peruana de biología*, 24, 155–162.
- Mol, J. A. N. H., & Ouboter, P. E. (2004). Downstream effects of erosion from small-scale gold mining on the instream habitat and fish community of a small neotropical rainforest stream. *Conservation Biology*, 18, 201–214.
- Moore, I. D., Grayson, R. B., & Ladson, A. R. (1991). Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. *Hydrological Processes*, 5, 3–30.
- Nie, Y., Swaisgood, R. R., Zhang, Z., Hu, Y., Ma, Y., & Wei, F. (2012). Giant panda scent-marking strategies in the wild: Role of season, sex and marking surface. *Animal Behaviour*, 84, 39–44. <https://doi.org/10.1016/j.anbehav.2012.03.026>
- Palmeirim, A. F., Peres, C. A., & Rosas, F. C. W. (2014). Giant otter population responses to habitat expansion and degradation induced by a mega hydroelectric dam. *Biological Conservation*, 174, 30–38. <https://doi.org/10.1016/j.biocon.2014.03.015>
- Pelice, F. M., Azevedo-Santos, V. M., Vitule, J. R. S., Orsi, M. L., Lima Junior, D. P., Magalhães, A. L. B., Pompeu, P. S., Petrere, M., & Agostinho, A. A. (2017). Neotropical freshwater fishes imperilled by unsustainable policies. *Fish and Fisheries*, 18, 1119–1133.
- Pettorelli, N., Laurance, W. F., O'Brien, T. G., Wegmann, M., Nagendra, H., & Turner, W. (2014). Satellite remote sensing for applied ecologists: Opportunities and challenges. *Journal of Applied Ecology*, 51, 839–848.
- Pimenta, N. C., Antunes, A. P., Barnett, A. A., Macedo, V. W., & Shepard, G. H., Jr. (2018). Differential resilience of Amazonian otters along the Rio Negro in the aftermath of the 20th century international fur trade. *PLoS One*, 13, e0193984.
- Pimenta, N. C., Gonçalves, A. L. S., Shepard, G. H., Macedo, V. W., & Barnett, A. P. A. (2018). The return of giant otter to the Baniwa Landscape: A multi-scale approach to species recovery in the middle Içana River, Northwest Amazonia, Brazil. *Biological Conservation*, 224, 318–326.
- Pimm, S. L., Alibhai, S., Bergl, R., Dehgan, A., Giri, C., Jewell, Z., Joppa, L., Kays, R., & Loarie, S. (2015). Emerging technologies to conserve biodiversity. *Trends in Ecology & Evolution*, 30, 685–696.
- Queiroz, N., Humphries, N. E., Couto, A., Vedor, M., da Costa, I., Sequeira, A. M. M., Mucientes, G., Santos, A. M., Abascal, F. J., Abercrombie, D. L., Abrantes, K., Acuña-Marrero, D., Afonso, A. S., Afonso, P., Anders, D., Araujo, G., Arauz, R., Bach, P., Barnett, A., ... Sims, D. W. (2019). Global spatial risk assessment of sharks under the footprint of fisheries. *Nature*, 572, 461–466.
- R Development Core Team. (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. <http://www.R-project.org>
- Rabus, B., Eineder, M., Roth, A., & Bamler, R. (2003). The shuttle radar topography mission – A new class of digital elevation models acquired by spaceborne radar. *ISPRS Journal of Photogrammetry and Remote Sensing*, 57, 241–262.
- Rosas, F. C. W., Ramalheira, C. S., Bozzetti, B. F., Palmeirim, A. F., Cruz, A. D., Pathek, D. B., & Cabral, M. M. M. (2015). Sleeping sites used by giant otters (*Pteronura brasiliensis*) in the Balbina hydroelectric reservoir, Central Brazilian Amazon. *Aquatic Mammals*, 41, 143–148.
- Rosas, F. C. W., Zuanon, J. A. S., & Carter, S. K. (1999). Feeding ecology of the giant otter, *Pteronura brasiliensis*. *Biotropica*, 31, 502–206.
- Ruwaimana, M., Satyanarayana, B., Otero, V. M., Muslim, A., Syafiq, A. M., Ibrahim, S., Raymaekers, D., Koedam, N., & Dahdouh-Guebas, F. (2018). The advantages of using drones over space-borne imagery in the mapping of mangrove forests. *PLoS One*, 13, e0200288.
- Salo, J., Kalliola, R., Hakkinen, I., Makinen, Y., Niemela, P., Puhakka, M., & Coley, P. D. (1986). River dynamics and the diversity of Amazon lowland forest. *Letters to Nature*, 332, 254–258.
- Smith, A. (2010). Image segmentation scale parameter optimization and land cover classification using the Random Forest algorithm. *Journal of Spatial Science*, 55, 69–79.
- Staib, E., & Schenck, C. (1994). Giant otters and ecotourism in Peru. *IUCN Otter Specialist Group Bulletin*, 9, 7–8.
- Strandburg-Peshkin, A., Farine, D. R., Crofoot, M. C., & Couzin, I. D. (2017). Habitat and social factors shape individual decisions and emergent group structure during baboon collective movement. *eLife*, 6, e19505.
- Stronza, A., & Pêgas, F. (2008). Ecotourism and conservation: Two cases from Brazil and Peru. *Human Dimensions of Wildlife*, 13, 263–279.
- Szantoi, Z., Smith, S. E., Strona, G., Koh, L. P., & Wich, S. A. (2017). Mapping orangutan habitat and agricultural areas using

- Landsat OLI imagery augmented with unmanned aircraft system aerial photography. *International Journal of Remote Sensing*, 38, 2231–2245.
- Terborgh, J. W., Davenport, L. C., Belcon, A. U., Katul, G., Swenson, J. J., Fritz, S. C., & Baker, P. A. (2018). Twenty-three-year timeline of ecological stable states and regime shifts in upper Amazon oxbow lakes. *Hydrobiologia*, 807, 99–111.
- Tucker, M. A., Böhning-Gaese, K., Fagan, W. F., Fryxell, J. M., van Moorter, B., Alberts, S. C., Ali, A. H., Allen, A. M., Attias, N., Avgar, T., Bartlam-Brooks, H., Bayarbaatar, B., Belant, J. L., Bertassoni, A., Beyer, D., Bidner, L., van Beest, F. M., Blake, S., Blaum, N., ... Mueller, T. (2018). Moving in the Anthropocene: Global reductions in terrestrial mammalian movements. *Science*, 359, 466–469.
- Weinberger, I. C., Muff, S., de Jongh, A., Kranz, A., & Bontadina, F. (2016). Flexible habitat selection paves the way for a recovery of otter populations in the European Alps. *Biological Conservation*, 199, 88–95.
- Woodget, A. S., Austrums, R., Maddock, I. P., & Habit, E. (2017). Drones and digital photogrammetry: From classifications to continuums for monitoring river habitat and hydromorphology. *Wiley Interdisciplinary Reviews: Water*, 4, e1222.
- WorldPop. (2018). The spatial distribution of population in 2018, Peru. WorldPop (www.worldpop.org – School of Geography

and Environmental Science, University of Southampton; Department of Geography and Geosciences, University of Louisville; Departement de Geographie, Universite de Namur) and Center for International Earth Science.

SUPPORTING INFORMATION

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

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