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A Comparative Analysis of Drone and Boat Monitoring for the Endangered Bolivian River Dolphin

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Abstract

Accurate population monitoring is essential for effective wildlife conservation. This study compares the effectiveness of drone-based vs traditional boat-based methods for assessing an endangered Bolivian river dolphin (*Inia geoffrensis boliviensis*; BRD) population in Bolivia. Data were collected using high-resolution video recorded with a DJI Mavic 2 zoom drone and standardized methodologies for boat surveys. Two mixed-effects linear models incorporating Poisson and negative binomial error structures were used to compare counts obtained from drone- and boat-based surveys. Results show that drone-based surveys detected 1.15% more individuals on average than boat-based surveys. Drone counts were higher at sites with larger group sizes, leading to congruent estimates. The aerial perspective that drones offer lets researchers overcome potential challenges from boat-based surveys—for example, difficulties related to confirming individual IDs because of limited visibility due to sun glare. Transitioning from boat- to drone-based surveys offers advantages such as reduced disturbance from placement closer to the animals and improved detection rates. Ethical considerations and responsible flight practices are crucial. Standardizing methodologies and prioritizing ethical research factors are key for successful implementation. Drone-based surveys offer a promising approach to enhance wildlife monitoring and conservation practices. This study is the first of this kind for Bolivia, a national natural heritage site, and contributes to the conservation and knowledge of the BRD.

Key Words: Bolivian river dolphin, drone-based monitoring, comparative methods, population estimation, wildlife conservation

Introduction

Monitoring population size is crucial for the conservation and management of wildlife. By detecting changes in population estimates, we can receive early warnings that help prevent the loss of species (e.g., Caughley, 1994; Mosnier et al., 2015; Bailes et al., 2018; Boyd & Punt, 2021). Fluctuations in population size can act as indicators of the impact of emerging or intensifying threats, as well as for the effectiveness of conservation efforts (e.g., Crimmins et al., 2014). To accurately measure these fluctuations, it is important that the methodologies employed by each study group are accurate, efficient, and comparable (Boyd & Punt, 2021).

In the past decade, unmanned aerial vehicles (UAVs), commonly known as drones, have become an accessible, safe, and efficient tool for capturing precise and reliable data of presence, distribution, and density (Hodgson et al., 2013; Angliss et al., 2018). Their use has grown due to their ability to rapidly survey areas from an aerial perspective, which allows for the detection of cryptic animals and the exploration of otherwise inaccessible areas (Fettermann et al., 2022). The ability to attach various sensors, such as thermal or acoustic sensors, as well as cameras and altimeters combined with their low cost is making them a popular tool for terrestrial wildlife monitoring (Nowak et al., 2018; Raoult et al., 2020). Furthermore, studies of marine cetaceans using drones offer a significant advantage by providing biological information at finer scales than what can be obtained through traditional aircraft such as airplane, helicopter, or higher-altitude satellite imagery (Clarke et al., 2021).

Since the mid-1950s, researchers have been estimating the population of South American river dolphins using traditional visual boat surveys, a practice that has continued for nearly four decades (Layne, 1958; Pilleri & Gihr, 1977; Magnusson et al., 1980; Best & da Silva, 1989; Herman et al., 1996). To address the unique fluvial characteristics of the Amazon region, researchers adopted a protocol proposed by Vidal (1997) that combined line and strip transects. Knowledge in the field expanded through the work of researchers such as Aliaga-Rossel (2002) in Bolivia, McGuire (2002) in Peru, Martin & da Silva (2004a, 2004b) in Brazil, and Gomez-Salazar et al. (2012) in Colombia. In recent years, efforts have intensified with robust statistical analyses generated by several researchers (Pavanato et al., 2016, 2019; Williams et al., 2016; Aliaga-Rossel & Guizada, 2017; Aliaga-Rossel & Guizada Duran, 2020a; Mosquera-Guerra et al., 2020; Paschoalini et al., 2020, 2021). However, large-scale studies of this type can be expensive and infrequent, which can affect monitoring efforts. Additionally, the presence of a research boat may cause different and unpredictable behavioral changes in group size and composition that could affect or possibly influence results (Dawson et al., 2008; Dwyer et al., 2014; Guerra et al., 2014; May-Collado & Quiñones-Lebrón, 2014; Guerra & Dawson, 2016).

The Bolivian river dolphin (*Inia geoffrensis boliviensis*; BRD) is an endangered species (da Silva & Martin, 2018) and the only cetacean in landlocked Bolivia, which was designated as a national natural heritage site for its uniqueness. Its distribution is restricted to the upper basin of the Madeira River, including tributary rivers in the Mamoré and Iténez sub-basins in Bolivia, extending up to the Teotonio rapids in Brazil (Aliaga-Rossel & McGuire, 2010; Gravena et al., 2015). Few studies have focused on the basic biology of the species. Instead, most research has utilized traditional, standardized boat-based counting techniques to conduct population surveys within the species range to estimate dolphin numbers and habitat use (e.g., Salinas-Mendoza, 2007; Aramayo, 2010; Aliaga-Rossel et al., 2012; Morales, 2012; Guizada & Aliaga-Rossel, 2016; Aliaga-Rossel & Guizada, 2017; Aliaga-Rossel & Guizada Duran, 2020b)

Therefore, identifying new methodological alternatives and testing them is important for comparing and identifying possible discrepancies between traditional population size estimates, as well as for finding cost-efficient long-term monitoring methods. This study represents a milestone as the first-ever comparison of drone-based data collection techniques with traditional boat-based methods for studying the endangered BRD in its unique and complex ecosystem. This research unveils innovative insights regarding the optimal monitoring modalities for the species. Throughout the study, a standardized assessment of various rivers within the BRDs' natural distribution habitats was conducted. The aim of this research was to evaluate the use of drones for improving population counts and obtaining more accurate numbers. By exploring the potential of drone technology, we aimed to enhance our understanding of its applicability and efficacy in ecological research, with a focus on achieving more precise population estimates of the BRD species.

Moreover, the advancement of drone-based methodologies, empowered by enhanced data acquisition capabilities, bears significant implications for future conservation and management initiatives aimed at protecting this highly endangered species. This technological advancement augments our ability to advocate for the welfare of this species and to sustain the intricately interdependent ecosystems they inhabit.

Methods

Study Area

The data correspond to four annual expeditions conducted in 2019, 2021 (covering two sub-basins), and 2022. Each expedition took place during the dry season of the respective year. Five rivers in the Mamoré and Iténez sub-basins, located in the Beni Department of Bolivia, were evaluated (Table 1).

These sub-basins form part of the Madeira sub-basin within the Amazon region. The average temperature in the area is 26.5ºC, and annual rainfall ranges from 1,200 to 2,400 mm per year (Aliaga-Rossel, 2002). The relative humidity varies from 60% in August to 77% in January and February (Pouilly & Beck, 2004). The hydrological patterns are directly influenced by precipitation, with peak water levels occurring between December and April, and the lowest levels between June and October (Aliaga-Rossel & Quevedo, 2011). The

Table 1. Survey counts conducted during the 2019, 2021, and 2022 expeditions in the Mamoré and Iténez Rivers' sub-basins during the dry season

River	Date	No. of overflights	Minutes analyzed
Tijamuchi	Aug. 2019	2	70
Mamoré	Aug. 2021	2	30
Isiboro	Aug. 2021	1	25
Pojije	Aug. 2021	1	25
San Martin	Aug. 2021	3	100
Blanco	Aug. 2021	1	25
Mamoré	July 2022	2	45
Apere	July 2022	1	25

riverbank vegetation exhibits typical characteristics of tropical gallery forests, which are intermittently interspersed with savannas. Cattle ranching, fishing, and small-scale agriculture are the main economic activities for human indigenous communities along the riverbanks. The Mamoré River is a whitewater type of Andean origin that is non-acidic, turbid, and of medium conductivity; it is also richer in nutrients and prey. This is one of the main rivers of the country, receiving several affluents and tributaries along its route. In contrast, the tributary rivers selected for this study can be characterized by mixed and clear waters, which are of local origin, acidic, lacking in suspended sediments, and have low conductivity. In both cases, the transparency of the water is low.

Drones were used to survey the Mamoré, Tijamuchi, Isiboro, Pojije, and Apere Rivers in the Mamoré sub-basin as well as the San Martin and Blanco Rivers in the Iténez sub-basin (Figure 1). The project consisted of two methodologies aimed at improving the counting of BRDs in a specific area by conducting boat and drone surveys simultaneously. This approach allowed for concurrent counting of animals and provided wider coverage of their range.

Boat Survey Method
Boat and drone surveys were conducted simultaneously. For the traditional boat transect, the standardized methodologies described and discussed in detail by Aliaga-Rossel (2002), Guizada & Aliaga-Rossel (2016), and Aliaga-Rossel & Guizada (2022b) were followed. The boat maintained a constant velocity ranging from 7 to 10 km/h in tributaries and 10 to 15 km/h in main rivers, with the speed influenced by water current. The transects were performed between 0700 and 1800 h, with a break of 1 to 2 h around noon. Transects had to be carried out under good visibility circumstances; and if the weather was unfavorable (rain or strong winds), they were temporarily interrupted. For each encounter with BRDs, the number of individuals was recorded, and several individuals within a radius of 25 m were considered a group. Two observers were stationed on each side of the boat's bow, giving 120° total coverage, each with a 60° angle of detection. To verify dolphin encounters, a third person observed and counted dolphins from the boat's stern.

The GPS location, time of day, river width, and group size of each sighting of BRDs were all noted. Observers recorded the number of dolphins

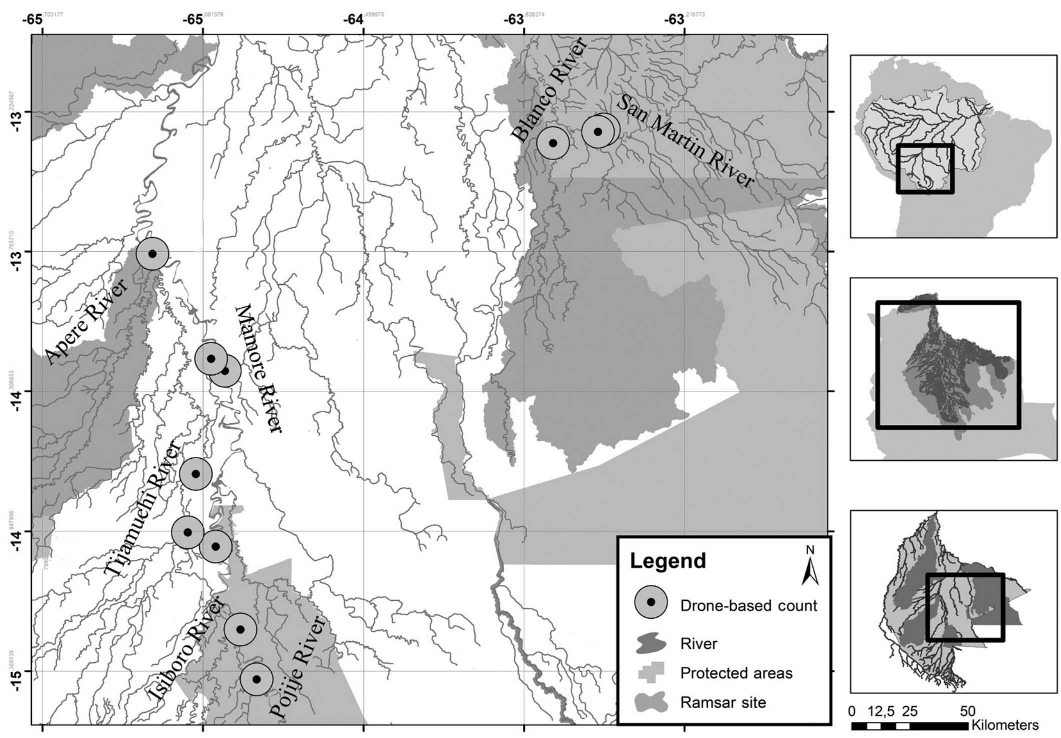

Figure 1. The study area comprises the drone surveys conducted in various tributary rivers within the Upper Madeira subbasin, which is located in the Beni Department, Bolivia.

per sighting whenever they observed one or more BRDs; the word "group" was used to describe a collection of individuals that were seen together or seemed gathered together. Sites where group sizes were greater than three individuals were selected for drone overflights. Additionally, control sites without BRD detections using conventional methods were randomly selected for drone overflights and recordings. The comparable data between the two methods correspond to a segment of the conventional transect 500 m upstream and 500 m downstream of the overflight point.

Drone Survey Method

Drone data collection employed a DJI Mavic 2 zoom equipped with four rotary-wing motors. Video recordings were captured in 4k resolution (4,096 × 2,160 pixels) at 30 frames per second. Each drone take-off was executed from the riverbank, preferably from beaches or open plains at least 500 m from the observation point, to minimize animal disturbance during take-off and to ensure a safe return. The drone took off after a 5-min wait to reduce any potential impact caused by the boat's arrival at the location. Flights were maintained at an altitude of 25 to 50 m above water level to minimize disturbances (Fettermann et al., 2019). The maximum flight distance from the starting point was 500 m, with flights lasting at least 15 min and at a maximum speed of 25 km/h. Weather conditions for flights were restricted to favorable environments, avoiding rain and ensuring light to moderate winds (less than 10 kts). The camera was positioned at a 25° to 35° angle relative to the horizon to reduce solar glare, following Barreto et al. (2021). Once the standardized altitude was achieved, the drone was manually navigated to the area of interest. Recordings were segmented into 5-min blocks to reduce file size.

Drone footage was played back at normal speed to retrieve the number of groups and each group's size. If necessary, the recording was paused to enlarge it or was played back frame-by-frame, carefully examining the recording to maximize detection of animals present. To ensure data accuracy, at least two observers performed the counts independently (i.e., blind counts), following the same methodology and using high-resolution monitors (Barreto et al., 2021; Fettermann et al., 2022; de Oliveira et al., 2023).

Permits and Regulations

The use of drones in the area adhered to the permissions obtained and reported to the National Aviation Authority (DGAC [Spanish acronym]), with the pilots holding valid aviation licenses and relevant certifications. The permissions were processed virtually through the designated platform (https://www.dgac.gob.bo/drones). The permits for navigating and counting dolphins through conventional methods (i.e., boat-based surveys) were governed by Research Permit MMAYA/VMABCCGDF/DGABP/MEG No. 0218/2022.

Data Analysis

We employed two mixed-effects linear models, incorporating Poisson and negative binomial error structures, using the glmmTMB function within the 'glmmTMB' package (Magnusson et al., 2017) in *R* (R Core Team, 2020) with a significance value of 0.05. The counting method, either boat- or drone-based, served as the predictor variable, while the rivers where the data were collected were treated as random intercepts in both mixed models. Model selection was based on the lowest Akaike Information Criterion (AIC) value, and validation was conducted using the 'DHARMa' package (Hartig, 2021).

Results

A total of 345 min of recordings were analyzed. The number of BRDs observed using the conventional (boat-based) method in each subsegment of the transect ranged from 0 to 19 (Table 2), while counts from aerial (drone-based) surveys varied from 1 to 49 BRDs, depending on the river (Table 2).

On average, drone-based counts produced a significant ($p < 0.05$) 1.15% more individuals confirmed (M = 9.2; SD = 9.37) over boat-based counts (M = 3.1; SD = 3.03) (Table 3; Figure 2). Drone counts were higher primarily at sites where group sizes were greater than three individuals resulting in congruent estimates between the two methods (Figure 2).

Table 2. Number of sightings accumulated with each method for each river

River	# BRD – boat-based	# BRD – drone-based
Tijamuchi	2	9
Mamoré	2	5
Isiboro	2	10
Pojije	6	18
San Martin	19	49
Blanco	0	1
Apere	4	6

Table 3. Results of the linear mixed-effect model fitted to explain the difference in the number of Bolivian river dolphins (*Inia geoffrensis boliviensis*; drone-based count surveys minus boat-based count surveys) observed depending on the river

Random effect	Variance	SD		
River	0.7138	0.8449		
Fixed effects	Estimate	SE	Z value	Pr(>|z|)
Intercept	0.7519	0.4676	1.608	0.1079
Method – Drone	1.1513	0.3553	3.240	0.0012*

*p value < 0.01

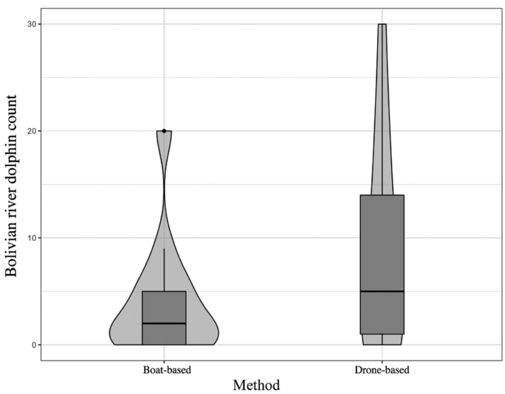

Figure 2. Violin graph of median group size recorded from boat- and drone-based (UAV) surveys from 20 independent Bolivian river dolphin (*Inia geoffrensis boliviensis*) group encounters between August 2019 and July 2022 at rivers in Beni Department, Bolivia

Discussion

Our results indicate that there was a significant difference in BRD counts using drones vs boat-based survey methods. These results support our initial hypothesis that drone-based studies are more accurate than boat-based surveys when documenting the number of individuals in dolphin groups. These findings are consistent with studies on dolphins that used an aerostatic method (Fürstenau Oliveira et al., 2017)—helicopters (Kelaher et al., 2019), and both airplanes and helicopters (Sucunza et al., 2022)—in Brazil. In these studies, accuracy and precision in population estimates were improved using aerial methods as compared to land- or boat-based observations.

Limitations and Advantages of Both Methods

Cetaceans are visible only for brief periods of time at the surface, which can lead to visually underestimating group sizes (Boyd et al., 2019). In contrast to some other species, BRDs are not acrobatic, and their surfacings to breathe are brief, usually exposing only part of the blowhole (Aliaga-Rossel, 2002; Aliaga-Rossel & Escobar-WW, 2020). Also, determining the exact number of individuals in a group can be challenging (Gerrodette et al., 2019) because the animals continue to move or surface more frequently or are simultaneously close to multiple individuals. Aerial perspectives offered by drone imagery can significantly decrease the chances of animals remaining unnoticed within the study area (Kelaher et al., 2019).

Identifying individual BRDs from a boat can be a daunting task, particularly in scenarios where multiple dolphins surface simultaneously, when there are calves within the group, or when these elusive creatures submerge and stay below the surface for prolonged periods (Aliaga-Rossel et al., 2006; Fürstenau Oliveira et al., 2017; Aliaga-Rossel & Escobar-WW, 2020; Fettermann et al., 2022). Furthermore, dolphins exhibit rapid movements and can change direction and speed when surfacing or diving, often asynchronously; and river dolphins can "u" turn instantly (Wilson et al., 1999), increasing the chances of error in counting, leading to over- or underestimates in population sizes.

In conventional boat-based methods, group sizes are initially estimated, typically in studies involving river dolphins, using the term "group" to refer to the total number of observed animals or an apparent aggregation. It is worth noting that this definition of a group differs from the traditional one and does not take into account the social cohesion or interactions of river dolphins being observed (Aliaga-Rossel, 2002). Subsequently, these estimates could be confirmed or adjusted using photo-identification techniques, although Trujillo (1994) has also discussed the efficacy of this method on river dolphins. However, this approach may not be equally applicable to river dolphins (Hupman et al., 2018) due to the species' shy nature and the turbidity of the water. Capturing complete images of every individual in a group is often unfeasible, especially in areas such as meanders, large curves, or lagoons. In contrast, drone-based surveys of small cetaceans offer the advantage of counting all individuals present and visible at or just below the surface, which proves particularly valuable when studying large groups that surface simultaneously (Fürstenau Oliveira et al., 2017; Fettermann et al., 2022).

Similar to Oliveira-da-Costa et al. (2020), we found that using high-resolution cameras and detailed analysis of recordings improved detection rates and allowed for better differentiation between individuals. Boat-based observers often tend to focus on isolated events at specific times, whereas drone counts allow for the observation of multiple clusters occurring simultaneously over a larger area. This ability to review the footage multiple times results in a more comprehensive assessment (Oliveira-da-Costa et al., 2020). Additionally, drones offer improved counting accuracy, particularly for groups larger than three individuals. The most extreme case was observed on the San Martin River where drone-based counts were 3.5 times greater than boat-based counts. Aliaga-Rossel & Escobar-WW (2020) also underwent similar experiences comparing a conventional survey methodology to direct captures of BRDs for rescue purposes. Following the complete extraction of individuals, they discovered that only approximately 40% of sightings matched the conventional estimates (n = 10 for conventional estimate; n = 26 for captures). Although the authors provided a detailed explanation about the unusual behavior of trapped dolphins, they highlighted the limitations of the method and the impossibility of seeing them in the murky river waters, suggesting that the standardized direct observation method commonly used may underestimate the size of river dolphin populations (see Figure S1; the supplemental figure for this article is available on the *Aquatic Mammals* website).

Environmental Influence

Environmental characteristics such as water type also influenced differences between drone- and boat-based counts. The San Martin and Blanco Rivers are part of the Iténez river basin that has clear water characteristics with reduced organic material and nutrients resulting in higher transparency compared to tributary rivers in the Mamoré sub-basin such as Tijamuchi, Isiboro, Mamoré, Apere, and Pojije that have white turbid waters (Charrière et al., 2004; Pouilly & Beck, 2004). The transparency of clear waters allows for more accurate counts from an aerial perspective even when river dolphins spend most of their time underwater. Because of this, environments with clear water conditions may be recommended more often for conducting drone studies related to behavior.

Technological Potential and Future Direction

The rapid technological advancements and their application in wildlife conservation have undeniably provided valuable contributions across various disciplines (Fürstenau Oliveira et al., 2017; Raoult et al., 2020; Fettermann et al., 2022). These tools have become more precise and readily available, thus increasing their potential. Nonetheless, it is crucial to ensure their ethical utilization as improper flight practices, such as flying at inappropriate altitudes or for extended durations, can disrupt the behavior of the studied fauna and potentially have detrimental effects.

Drones with short flight duration, known as multirotors, are being equipped with infrared and near-infrared cameras, enabling the measurement of temperature for animals visible from the air (Harvey et al., 2016; Wosnick et al., 2018). They can also carry laser altimeters to enhance precision in photogrammetry and to structure processing (Dawson et al., 2017). However, the enhancements in camera resolution and data management pose challenges as high-resolution videos generate substantial data, making field storage complex and more expensive (Raoult et al., 2020). Moreover, limited flight time due to battery life is a constraint, especially in consumer drones with flight times under 30 min (Raoult et al., 2020). Also, battery replacement interrupts monitoring and makes relocating animals of interest difficult (Raoult et al., 2020). Additionally, pilot fatigue can become an issue during manual flights. In remote areas without power supply, charging batteries can be challenging without extra replacements, increasing the cost of drone usage.

The incorporation of technology into wildlife research has the potential to enhance data quality; however, it also leads to the generation of larger datasets that typically require manual processing, resulting in increased time consumption and a higher risk of human errors (Oliveira-da-Costa et al., 2020). The development of machine learning techniques offers a complementary and potentially transformative approach. Machine learning can automate image analysis, mitigating these biases and streamlining data processing (Hodgson et al., 2017; Adams, 2018; de Oliveira et al., 2023). By leveraging these advancements, researchers can improve accuracy and enhance the overall efficiency of wildlife studies, paving the way for a more objective and data-driven future.

To embrace the rapid technological advancements, it is advisable for future studies to prioritize the standardization of specific methodologies tailored to each species under investigation while considering ethical research factors. Conducting studies using drones offers the advantage of reduced intrusiveness compared to traditional boat-based approaches (Mann et al., 2000) and increased precision in counting. Consequently, it is highly probable that drones will gradually supersede conventional boat-based studies, providing more comprehensive and reliable data for wildlife management and conservation purposes.

Conclusion

This study highlights the potential of drone-based surveys for assessing the endangered BRD populations. The use of drones offers several advantages over traditional boat-based methods, including increased accuracy in population estimates and reduced disturbance to the animals. By providing a higher-resolution aerial perspective, drones improve the detection of individuals, particularly in large groups. These findings suggest that drone-based surveys can play a crucial role in behavioral studies and further wildlife conservation efforts, providing more robust and reliable data for population assessments.

The successful implementation of drone-based surveys requires careful consideration of ethical research practices and responsible flight protocols. It is important to ensure that the use of technology in wildlife monitoring aligns with conservation goals and minimizes any potential negative impacts on the studied species. Standardizing methodologies and integrating advanced technologies, such as machine learning techniques, can further enhance data analysis and processing, ultimately improving the efficiency and effectiveness of wildlife studies. By embracing these technological advancements and incorporating ethical considerations, we can advance the conservation and management of BRDs and contribute to the overall understanding and protection of this endangered species.

Note: The supplemental figure for this article is available in the "Supplemental Material" section of the *Aquatic Mammals* website: https://www.aquaticmammalsjournal.org/supplemental-material.

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