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Advancing crocodiles conservation through aerial ecological monitoring with drones in West Africa

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Abstract
Crocodilians play an essential ecological role in West African freshwater ecosystems. However, monitoring them remains difficult due to their secretive behaviour and inaccessible habitats. This study examines the potential of using drones to monitor populations of the species *Crocodylus suchus* in a sacred pool in northern Benin. During the study, drone flights were conducted at various altitudes (15, 30 and 50 meters), speeds (0 and 2 meters per second) and approach angles (vertical and oblique). Environmental conditions such as land cover, contrast between the animals and the landscape, and observer effort were also assessed. A total of 54 flights were conducted to collect image and video sequences, which were analysed by four trained observers using Timelapse software. Generalised linear mixed models revealed that the probability of detection decreased significantly with altitude and visual contrast, but increased with observation time. Vegetation density had no significant impact on detectability. Interestingly, crocodiles showed no behavioural response to the presence of drones, even at low altitudes, suggesting high tolerance of aerial surveillance. These results highlight the potential of drones as a non-invasive, cost-effective, efficient tool for the ecological monitoring of crocodilians in agro-pastoral landscapes. Our study provides essential information for refining drone survey protocols and proposes a scalable approach to support evidence-based conservation strategies for *Crocodylus suchus* and similar species in West Africa.

Keywords: *Crocodylus suchus*, drone-based monitoring, detection probability, behavioural response, West African wetlands

Introduction
Crocodilians are apex predators that play an essential ecological role in West African freshwater ecosystems. The West African crocodile (*Crocodylus suchus*) is particularly notable among them for its wide but uneven distribution, and for its ability to adapt to both natural and artificial aquatic habitats, including agro-pastoral dams [1-3]. These dams are increasingly being built to provide rural communities with a permanent water source [4, 5] and also serve as vital habitats for crocodiles, particularly during the dry season. In northern Benin, for instance, crocodiles were found in up to 55% of the studied dams [6]. However, subsequent studies have reported alarming population declines linked to human activities, habitat fragmentation, and changes in hydrological regimes [7, 8].
Despite their ecological importance, monitoring and conserving crocodilian population's remains challenging due to their secretive behaviour, nocturnal nature, and preference for inaccessible aquatic environments [9, 10]. Traditional methods such as ground surveys using spotlights (GSS) and aerial counts by helicopter are logistically demanding, time-consuming and costly [11-14]. Furthermore, these approaches do not permit small-scale behavioural observations or post-survey image analysis.
Recent advances in drone technology have transformed ecological monitoring, offering a cost-effective, flexible and non-invasive alternative [15-17]. Unmanned aerial vehicles (UAVs) have proven highly effective in wildlife research, particularly for species detection [18], habitat mapping [19] and behavioural studies [20, 21]. Drones can acquire high-resolution images (e.g. 4K or 8K), perform long-distance autonomous flights and be deployed in previously inaccessible areas with minimal training, disturbance to wildlife and environmental impact [22-25].
Crocodilians are well suited to aerial surveys due to their tendency to bask openly along the edges of bodies of water, particularly during the dry season [26]. Drones have been successfully used to monitor various species of crocodilian, including the

American alligator *Alligator mississippiensis* [10, 27-30], mugger crocodile (*Crocodylus palustris*) [25], Nile crocodile (*Crocodylus niloticus*) [31, 32] and West African crocodile (*Crocodylus suchus*) [24], and the gharial (*Gavialis gangeticus*) [33]. These studies have provided new insights into nesting behaviour, population counts, habitat use, and biometric estimation using drone imagery [34].

Nevertheless, there are still some limitations: drones are restricted by factors such as battery life, data storage capacity and legal restrictions in certain countries [17, 18]. Furthermore, the accurate collection of biometric data via drone imaging requires careful calibration, since body measurements are frequently derived from partial visibility (e.g. only the head), which can result in estimation biases [24].

In light of the urgent need for cost-effective, reproducible and minimally invasive monitoring methods in West Africa, this study explores the potential of using drones to support crocodile conservation in agro-pastoral systems. With a focus on *Crocodylus suchus* in northern Benin, the study aims to evaluate the effectiveness of using drones to monitor crocodile populations. This knowledge will contribute to the development of evidence-based conservation strategies and long-term ecological monitoring protocols adapted to West African contexts.

Material and Methods

Study area

The study was conducted in a sacred pond in the municipality of Sinendé in the north of Benin. This culturally protected body of water is of ecological importance and is known for harbouring populations of West African crocodiles (*Crocodylus suchus*). The pond is surrounded by agro-pastoral landscapes with seasonal variations in vegetation. The site provides a potentially suitable habitat for crocodiles all year round. Fig. 1 shows the study environment.

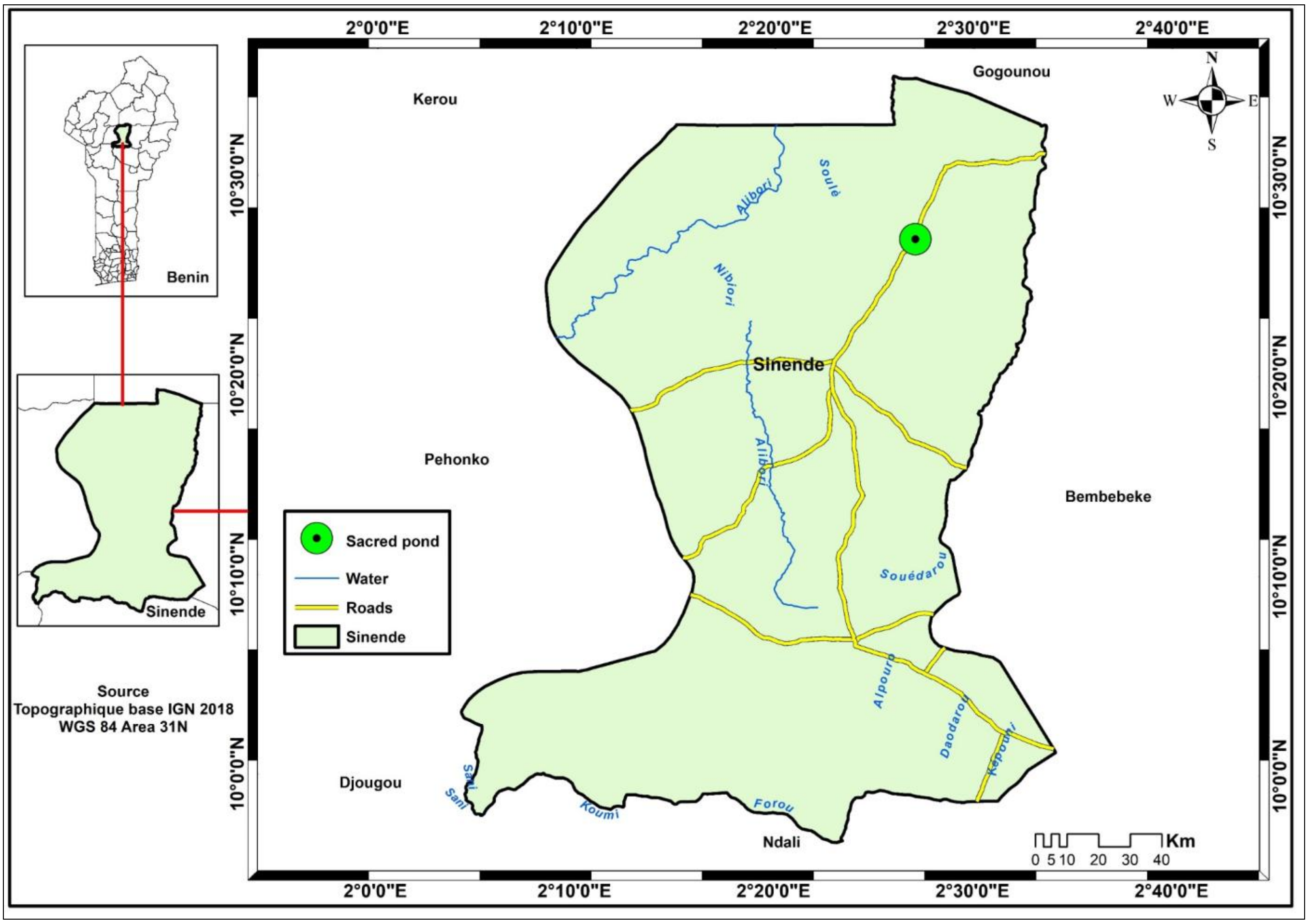

Fig 1: Geographical location of the sacred crocodile pond of Sinendé

We used a DJI Mini 3 drone equipped with a 4K RGB camera for all aerial observations. This drone has a 1/1.3-inch CMOS sensor and can capture 48 MP still images and UHD videos. It has GPS-assisted flight stabilisation and automatic trajectory programming. Flights were carried out manually and semi-autonomously using the DJI Fly and DJI Flight Planner apps in suitable weather and lighting conditions.

Data collection

Data were collected over six days between December 2024 and January 2025, with each observation day separated by a three-day interval. A stratified repeated measures protocol was implemented to assess the influence of drone flight parameters, environmental conditions and observer biases on the detection of crocodiles in images and videos.

Each sampling day comprised three drone flight sessions: morning (6:30-9:30 am), midday (11:00 am-1:30 pm) and late afternoon (4:00-6:30 pm). During each session, at least three complete passes over the pond were made, following circular trajectories that matched the pond's shape, in order to cover the entire area, including the banks.

Three main parameters were tested directly in the field: altitude, flight speed, and the drone's angle of approach. These factors are known to influence both the ability to detect animals and their behavioural responses [24, 35, 36].

Three altitudes were tested: 15 m, 30 m, and 50 m above the pond. Each flight session began at the highest altitude, gradually descending to minimise initial disturbance. Two speeds were compared: hovering (0 m/s) and slow flight (2 m/s); the latter simulating a typical search [15]. Two approach angles were also used: vertical (90°) and oblique (approximately 45°), to assess their influence on lateral visibility and crocodile reactions [15, 37].

For each combination of altitude, speed, and angle, the on-board camera took a video of approximately three minutes and ten photographs.

In the laboratory, the visual contrast between the colour of the crocodile and its environment (in the water or on the bank) was assessed using the collected images. The observers defined three levels of contrast: low (0), medium (1) and high (2).

Vegetation cover was also analysed from the images. A density index was assigned on a scale of 1 to 4, corresponding to visual obstruction of 0-25%, 25-50%, 50-75%, and 75-100% respectively. This enabled the impact of vegetation on the ability to detect animals to be quantified.

The images and videos obtained were then analysed using Timelapse Image Analysis software. This software enabled precise annotation of observations according to the flight parameters used. Each observer processed the sequences independently and the results were compared to measure consistency.

For each sequence, the time of day (morning, midday or afternoon) was noted, as well as how long each observer spent analysing the images (in seconds), again using the software.

The crocodiles' reactions were classified into three categories: (1) no reaction, (2) moving to another location and (3) rapidly immersing themselves in water.

To minimise observer bias, a standardised method inspired by [38] work on large mammals and [37] work on birds was employed. Four observers specialising in wildlife management were mobilised. Before starting the analysis, they participated in a calibration session involving the projection of images depicting various parts of the crocodile's anatomy. This step aimed to standardise their recognition criteria and improve the accuracy of identifying individuals from images and videos.

Statistical analysis

We evaluated the influence of the parameters Altitude, Observer, Contrast, Land cover, Observer time, and Times of day on animal detection.

Table 1 summarises the different variables used in our models.

Table 1. Summary of Predictor Variables for Generalized Linear Mixed Models (GLMM)

Variable	Nature	Levels/Units	Type	Characteristics
Altitude	Continuous	Meter (m)	Independent	Flight parameters
Observer	Categorical	Observer1 - Observer4	Random effect	Observer bias
Observer time	Continuous	Second (s)	Independent	Operational
Times of day	Categorical	Morning and Afternoon	Independent	Temporal
Contrast	Categorical	High, Low, Middle	Independent	Environmental
Land cover	Categorical	Percentage %	Independent	Environmental
Animal detection	Count	Number of Detection	Dependent	Ecological

First, we checked whether the only continuous predictive variable, the observers' observation time, followed a normal distribution. To do this, we used the Shapiro-Wilk test in R 4.2.3 (R Core Team, 2023). The result of the test indicated a significant deviation from normality ($W = 0.77772$, $p = 2.128e-13$), showing that this variable does not follow a normal distribution.

We then examined multicollinearity between the explanatory variables (altitude, observer, observation time and land cover type) using the check_collinearity function from the performance package [39]. All variance inflation factor (VIF) values were below 5, indicating no problematic collinearity between the predictors.

We then assessed the dispersion of the response variable by fitting a Poisson model. The obtained dispersion parameter was 7.99, revealing significant over dispersion. To correct for this, we fitted a generalised linear mixed model (GLMM) with a negative binomial distribution using the glmmTMB package [40]. This model yielded a dispersion parameter of 1.30, indicating a good fit.

We then used this GLMM to test the effects of altitude, observer identity, observation time and vegetation cover on crocodile detection. We included observer identity as a random effect to account for potential variability related to each individual. The other variables were considered fixed effects.

To identify the most informative models, several candidate models were constructed, including interaction effects where relevant. Automatic model selection and multi-model inference were performed using the 'dredge' function in the 'MuMIn' package [41]. The models were ranked according to their Akaike information criterion corrected for small samples (AICc), and only those with a ΔAICc <10 were considered plausible [42-44].

Finally, we performed a weighted average of the models using the model. avg function from the same package, taking into account model uncertainty and associated weights. We reported the conditional mean values of the estimated coefficients to provide a robust and balanced estimate of the effect of the predictors [41].

Results

Assessment of detection probability as a function of flight and environmental variables

Crocodile detection probability was significantly influenced by altitude, contrast level, and observer effort, while land cover type showed no significant effect. Relative to the baseline conditions (low altitude at 15 m, high contrast, and reference observer time), detection rates declined markedly at higher elevations. Specifically, detection at 50 m altitude was significantly lower (estimate = -0.48, p<0.001), indicating that Crocodile activity or detectability decreases with increasing altitude. The reduction observed at 30 m altitude was marginally non-significant (estimate = -0.20, p = 0.056), suggesting a trend towards diminished detection at mid-elevations.

Contrast level also had a strong effect on Crocodile detection. Compared with the high contrast class, detection probabilities were significantly reduced in both low (estimate = -0.53, $p<0.001$) and middle contrast environments (estimate = -0.32, $p = 0.001$).
Observer time positively influenced detection rates (estimate = 0.12, $p = 0.002$), consistent with increased survey effort or duration improving detection success. Conversely, land cover categories (1 to 4) did not significantly affect detection probability, indicating that, within the context of this study, habitat type was less critical than altitude or contrast for observing Crocodiles.
Fig. 2 shows the estimated effect sizes of the predictors influencing the detection probability of *Crocodylus suchus*, as obtained from the GLMM.

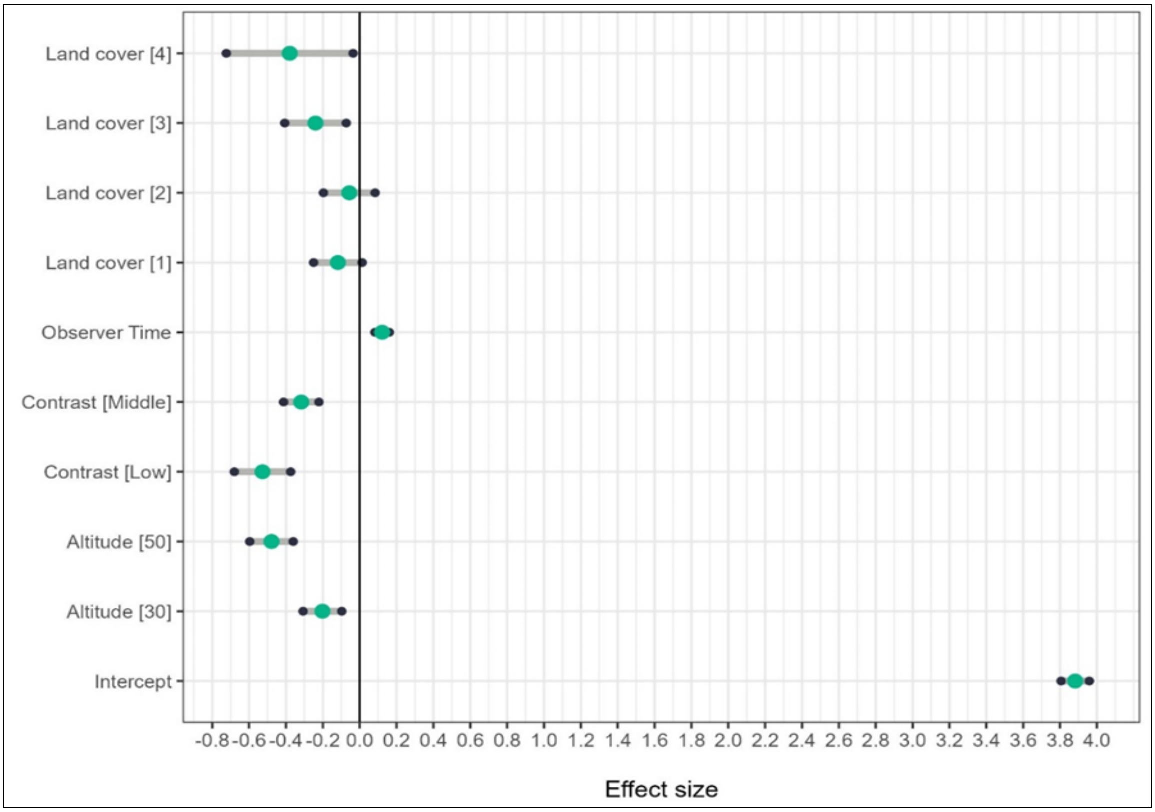

Fig 2. Estimated effect sizes of the predictors influencing the detection probability of *Crocodylus suchus,* as obtained from the GLMM.

Fig. 3 shows an aerial photograph taken during hovering at different altitudes.

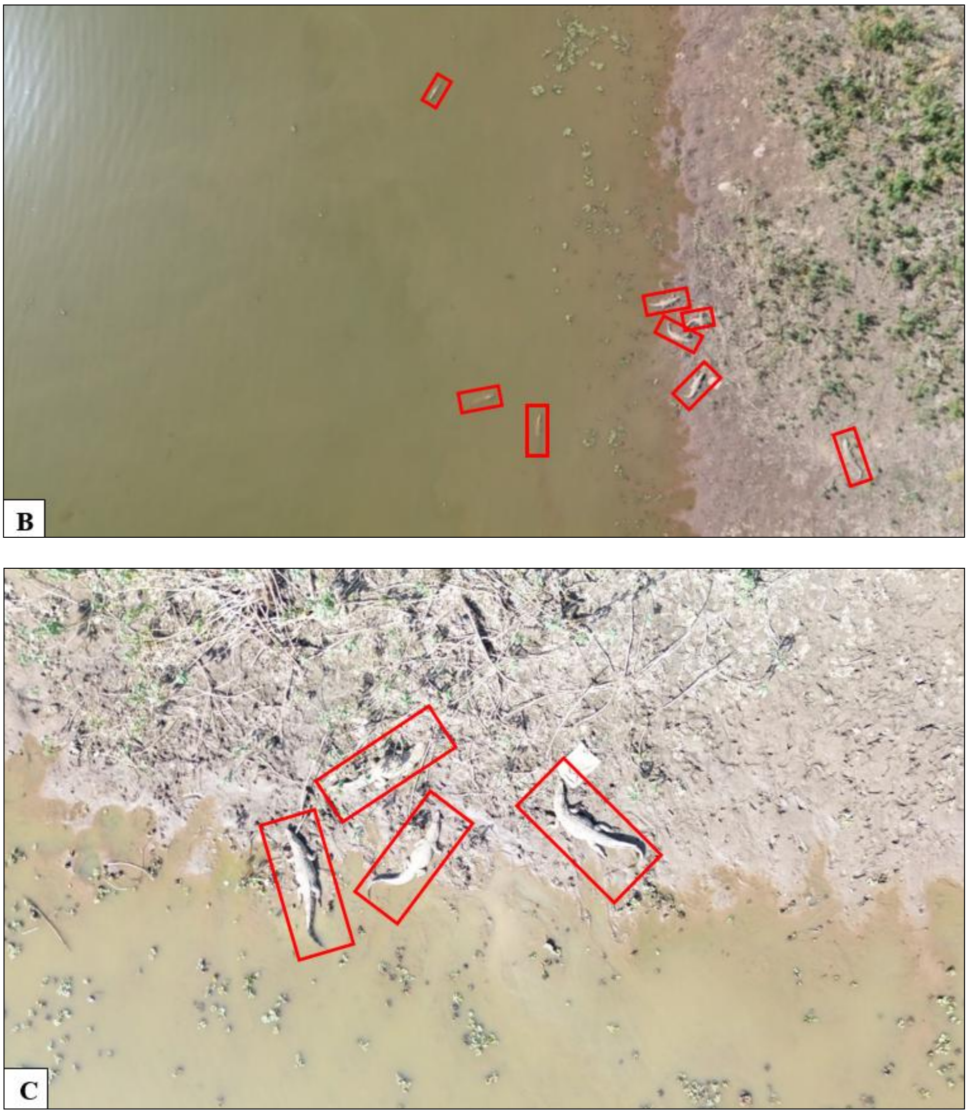

Fig 3: Aerial photographs taken during vertical hover: (a) 50 m; (b) 30 m; (c) 15 m

Behavioural assessment of crocodiles in response to drone flights: A total of 54 flights were carried out. Despite the variety of flight conditions tested (e.g. altitude, speed and angle of approach), no flight-related behaviour or disturbance was observed.

More specifically, no individual exhibited escape or immersion behaviour during or after the flyover. This consistent lack of reaction was observed regardless of the drone's altitude (including during flights at altitudes as low as 5 metres), speed (stationary or slow at 2 m/s), approach angle (vertical or oblique), time of day (morning, midday or afternoon) or animal position (in the water or on the bank).

Analysis of the videos and photographs, validated by four independent observers, revealed no signs of stress or avoidance, even when individuals were isolated or exposed on the banks**.**

Discussion

Our results are consistent with those of similar studies conducted on other cryptic species such as *Fregata ariel*, *Thalasseus bergii* and *Hippopotamus amphibius* [45, 46] semi-aquatic wetland species showing that the probability of crocodile detection decreases with altitude. At 50 meters, the reduction in detection is significant (p<0.001), suggesting that an altitude below 30 meters is preferable for maximising the identification of individuals. These results are comparable to those obtained for semi-aquatic reptiles and even some large mammals [47].

The visual contrast between the animal and its environment was also found to be a determining factor in detection. Detection rates were significantly higher in contexts with high visual contrast, particularly when the crocodiles were on light-coloured or lightly shaded riverbanks. Conversely, dense floating vegetation and shaded banks limited visibility; however, vegetation cover itself did not have a statistically significant effect in our model.

The effect of analyst observation time was also significant (p = 0.002), highlighting the importance of post-flight analysis in automated or semi-automated detection protocols [46]. This confirms that human expertise remains essential for identifying animals in images where only part of the body is visible, even with powerful tools.

Furthermore, behavioural results show that *Crocodylus suchus* is highly tolerant of drones at very low altitudes (up to 5 m), exhibiting no observable behavioural reaction. This corroborates previous studies indicating that crocodilians are relatively indifferent to aerial disturbances, particularly in open or semi-open habitats [9, 10, 24]. Unlike other wildlife groups, such as primates or birds, which are often sensitive to drone noise or shadows [35, 48], crocodiles seem largely unaffected by this type of disturbance.

This lack of reaction can be explained by several factors.

Firstly, the morphology and physiology of crocodiles suggest low sensitivity to the high-frequency sounds emitted by low-power drones [24]. Secondly, their familiarity with aerial stimuli in open environments could lead to habituation, particularly in areas where human activities such as noise, overflights and fishing are frequent [20].

Finally, the absence of observed behavioural reactions is advantageous for long-term ecological monitoring protocols. Unlike invasive capture or observation methods, drone flights allow data to be collected without disturbing the animals, thereby improving the reliability of behavioural and demographic estimates [15, 17]. These results reinforce the idea that drones are an ethical, effective, and non-intrusive method of monitoring crocodilians, particularly in sensitive contexts such as sacred ponds or protected areas.

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