



SAFARI CLUB INTERNATIONAL FOUNDATION



LEOPARD DENSITY AND DISTRIBUTION ACROSS BOTSWANA

A National Baseline for Conservation and Management

FINAL REPORT 2026

Final Report

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2026

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This report was prepared by Safari Club International Foundation (SCIF) for the Botswana Department of Wildlife and National Parks (DWNP) as part of the collaborative national leopard research and monitoring initiative undertaken by SCIF and DWNP.

The findings, analyses, and recommendations presented herein are intended to support evidence-based leopard conservation, sustainable management, and long-term population monitoring in Botswana.

African Big Cats Research and Conservation Strategy
Safari Club International Foundation
2026



Female leopard with cub captured on camera in CKGR (May 2023)

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Finally, we recognize the broader conservation and scientific community in Botswana for its continued commitment to leopard conservation and sustainable wildlife management. The information generated through this survey provides an important scientific baseline for future monitoring, management planning, and conservation decision-making.

African Big Cats Research and Conservation Strategy
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EXECUTIVE SUMMARY

- This study provides a national-scale assessment of African leopard (*Panthera pardus pardus*) density and distribution across Botswana and establishes a quantitative baseline for future conservation, management, and monitoring by the Department of Wildlife and National Parks (DWNP).
- Camera-trap surveys were conducted across 20 sites, using more than 1,000 camera stations and recording 1,424 leopard detections representing 434 identified individuals. Spatially Explicit Capture–Recapture (SECR) models were used to estimate site-specific densities for 19 sites, complemented by national models of predicted density and occupancy.
- Leopard abundance varies markedly across Botswana. Site-specific densities ranged from 0.15 to 2.74 leopards/100 km².
- Several areas support comparatively high leopard densities and may represent important population strongholds. The highest estimates occurred at NG28 (2.74 leopards/100 km²), CKGR (2.67), NG49 (2.30), and NG34 (1.95). Maintaining habitat quality, prey populations, connectivity, and appropriate levels of mortality in these areas should be an important conservation consideration.
- Low-density populations require context-specific interpretation. Low density does not necessarily indicate population decline or poor conservation status, as ecological productivity, prey availability, habitat conditions, and competition can naturally limit abundance. Where low densities are unexpected, additional evaluation of prey availability, human–leopard conflict, habitat change, and human-caused mortality is warranted.
- The precision of the SECR estimates, described by the coefficient of variation (CV), provides an explicit basis for determining their management value. For this study, estimates with CV <30% are considered sufficiently precise to inform DWNP management decisions, including quota allocation, when considered together with other relevant biological and management information.
- Sites density estimates with CV >30% remain informative but carry greater uncertainty. Additional or repeated sampling should be prioritized where precise abundance estimates are needed for management.
- Quota decisions should nevertheless also consider female density, previous harvest, problem-animal removals and other mortality, and connectivity rather than converting density directly into an

allowable offtake. Population trends should be considered when repeated density estimates become available.

- The national predicted-density map extends the site-level results to the broader landscape covering approximately 579,075 km² and producing a median national abundance estimate of 6,262 leopards (95% CI: 5,676–6,849) in Botswana.
- This density map identifies broad spatial patterns in expected abundance, including potential leopard population strongholds, and provides a valuable tool for national planning and prioritizing future surveys.
- The occupancy map demonstrates that leopards remain broadly distributed across Botswana and provides information complementary to density. Density identifies where leopard abundance is concentrated, whereas occupancy identifies the broader distribution of the species and landscapes potentially important for dispersal and population connectivity. Conservation planning should therefore consider both high-density populations and the intervening occupied landscapes that help maintain a connected national population.
- These results provide the foundation for adaptive leopard management by DWNP. The SECR density estimates establish the baseline for leopard population status and estimates, , especially where estimates have greater precision (e.g. CV <30%). These estimates can be used to inform DWNP management decisions, including quota allocation, when considered together with other relevant biological and management information.
- Future repeated standardized SECR surveys could determine whether populations are stable, increasing, or declining and allow quotas and other management actions to be adjusted accordingly.

INTRODUCTION AND JUSTIFICATION

The African leopard (*Panthera pardus pardus*) remains one of Africa's most recognizable large carnivores and an iconic member of the "Big Five." Although the species retains one of the broadest distributions of any large felid (Stein and Hayssen 2013), leopard populations have declined across much of their range due to habitat loss and fragmentation, prey depletion, increasing human populations, illegal killing, human-wildlife conflict, and unsustainable exploitation in some regions (Jacobson et al. 2016; Havmøller et al. 2021; Searle et al. 2020; Stein et al. 2020). These pressures have resulted in localized population declines, range contraction, and increasing fragmentation, highlighting the need for robust scientific information to guide conservation and sustainable management.

Long-term conservation and sustainable management require standardized, repeatable monitoring programs capable of detecting changes in population status over time. Repeated surveys using consistent sampling designs enable wildlife managers to establish reliable baselines, evaluate the effectiveness of management interventions, identify emerging threats, and adapt conservation and harvest strategies as ecological and socio-economic conditions change. Such monitoring is particularly important in heterogeneous landscapes where land use, habitat quality, prey availability, protection status, and human activities vary across space, often resulting in substantial differences in leopard density among management units. Consequently, effective leopard conservation requires a landscape-scale approach that recognizes the influence of multiple land uses on population persistence and connectivity.

This broader perspective is especially important because a substantial proportion of Africa's leopards occur outside formally protected areas (Hunter et al. 2013), where their persistence depends on compatible land-use practices and effective management across working landscapes (Jacobson et al. 2016; Stein et al. 2020). Limiting population assessments to protected areas can therefore provide an incomplete and potentially misleading understanding of regional population status. Robust estimates of leopard density are needed across the full spectrum of land uses—including protected areas, communal lands, safari hunting concessions, commercial ranches, and privately managed wildlife properties—to support landscape-level conservation planning, evaluate the contribution of different management systems to leopard persistence, and provide standardized, comparable estimates that accurately characterize variation in leopard density across landscapes and through time.

The study of leopard populations remains challenging because leopards occur at naturally low densities, occupy large home ranges, and exhibit secretive, predominantly nocturnal behavior. Reliable estimates of leopard population density derived from standardized sampling designs and rigorous analytical methods are essential for landscape-level conservation planning, evaluating the contribution of different land-use

systems to leopard persistence, and supporting evidence-based management decisions. Over the past two decades, systematic camera-trap surveys combined with Spatially Explicit Capture-Recapture (SECR) models have become the accepted standard for estimating densities of individually recognizable carnivores. By explicitly incorporating the spatial locations of detections and individual encounter histories, SECR models provide unbiased and repeatable estimates of population density while accounting for imperfect detection. These methods have been widely adopted throughout Africa and are now considered best practice for long-term leopard monitoring and conservation planning (Royle et al. 2014; Efford 2022).

Recognizing this need, the Safari Club International Foundation (SCIF), in partnership with the Botswana Department of Wildlife and National Parks (DWNP), initiated Botswana's first standardized nationwide leopard population density survey based on systematic camera-trap surveys and SECR analyses. Between September 2022 and December 2024, surveys were completed at 20 sampling sites spanning approximately 22,000 km² and representing a wide range of habitats and land-use types, including protected areas, wildlife management areas, safari hunting concessions, communal lands, and privately managed wildlife properties. The project established the first standardized national baseline of leopard density across Botswana using a repeatable scientific framework. The results presented in this report provide an objective foundation for the development of future population monitoring programs, evaluation of management interventions, quota setting where appropriate, and evidence-based conservation planning to ensure the long-term persistence and sustainable management of Botswana's leopard populations.

OBJECTIVES

- To generate robust estimates of African leopard population density across Botswana.
- To assess the current distribution of African leopards within Botswana, including extant, possibly extirpated, and extirpated populations.
- To compare leopard density and population size across eco-regions, habitat types, land-use systems, and management categories (e.g. hunting concessions, communal lands, conservation areas, and wildlife farms).
- To synthesize demographic information (e.g., density, sex ratio, age structure) from recent leopard studies.
- To provide research findings to support the development of science-based recommendations for the Botswana Ministry of Environment, Wildlife, and Tourism, facilitating coordinated leopard management and the establishment of sustainable harvest quotas.
- To share project findings with relevant partners in support of the long-term conservation of leopards in Botswana and the broader Southern African region.

STUDY AREA

Botswana is a largely semi-arid country in southern Africa, characterized by extensive open landscapes, low and highly variable annual rainfall, and strong spatial and temporal variation in water availability. Much of the country is covered by savanna ecosystems, ranging from relatively open grasslands and shrublands to woodland-dominated landscapes, with vegetation structure and productivity strongly influenced by rainfall, soil characteristics, fire, herbivory, and access to permanent or seasonal water sources. The country's major ecological systems include the Okavango Delta and surrounding wetlands in the northwest, the extensive Kalahari landscapes of central and western Botswana, the Chobe–Linyanti region in the north, and the more open savanna and agricultural landscapes of eastern and southeastern Botswana. These environmental gradients support diverse and abundant wildlife communities and provide habitat for leopard populations across much of the country.

Botswana's landscape is also characterized by a diverse mosaic of land-use and wildlife-management systems. Large areas of the country are managed for wildlife conservation and sustainable wildlife utilization, while other areas comprise communal lands, private and commercial wildlife farms, and designated hunting concessions. The intensity and type of human activity, livestock production, wildlife management, tourism, and hunting vary substantially among these land-use systems. Consequently, leopards occur in landscapes subject to markedly different levels of habitat protection, prey availability, human activity, and management intervention. This variation provides an important opportunity to examine leopard population density in relation to different management and land-use contexts.

Twenty focal areas (Figure 1) were selected by the Botswana Department of Wildlife and National Parks (DWNP) for sampling to address key management priorities and existing knowledge gaps regarding leopard population status across the country. Selection of focal areas considered several factors, including geographic distribution, variation in land-use practices, regional management priorities, and the availability of information from previous leopard surveys.

Collectively, the 20 focal areas represented four broadly defined land-use categories recognized by the DWNP: hunting concessions, communal areas, conservation areas, and wildlife farms (Figure 2). These categories encompass substantially different management objectives and patterns of human activity. Hunting concessions are primarily managed under wildlife-utilization frameworks, while conservation areas place greater emphasis on wildlife protection and biodiversity conservation. Communal areas generally support a combination of livestock production, human settlement, and wildlife use, whereas wildlife farms represent privately managed properties where wildlife conservation and utilization occur within predominantly fenced landscapes.

The sampling framework was designed to provide a standardized assessment of leopard populations across this heterogeneous landscape. By distributing sampling sites across different regions and land-use categories, the survey incorporated variation in habitat conditions, prey communities, levels of human activity, and management regimes. This approach was particularly important for evaluating whether differences in leopard density were associated with land-use and management context rather than being restricted to a single type of landscape.

The 20 focal areas therefore provided a broad representation of the ecological and management conditions under which leopards occur in Botswana. Standardized camera-trap sampling and Spatially Explicit Capture–Recapture (SECR) analysis across these areas generated comparable estimates of leopard density among sites and land-use categories. In addition to providing a national baseline of leopard population density, the resulting dataset establishes a framework for evaluating spatial variation in leopard populations and supporting future monitoring, management decisions, and adaptive conservation planning by the DWNP.

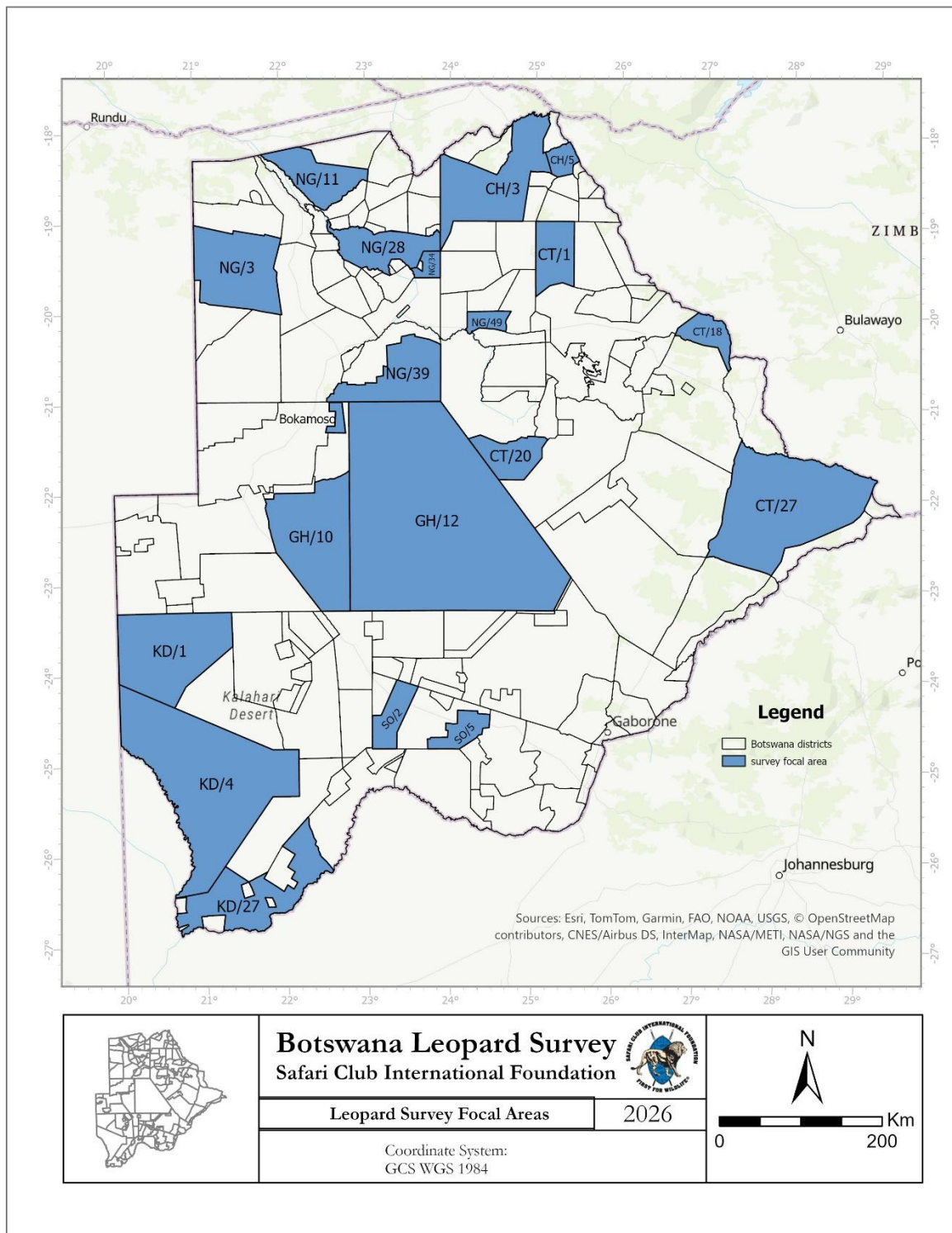


Figure 1. Leopard survey focal areas in Botswana, SCIF Botswana Leopard Survey. Areas sampled between September 2022 and December 2024.

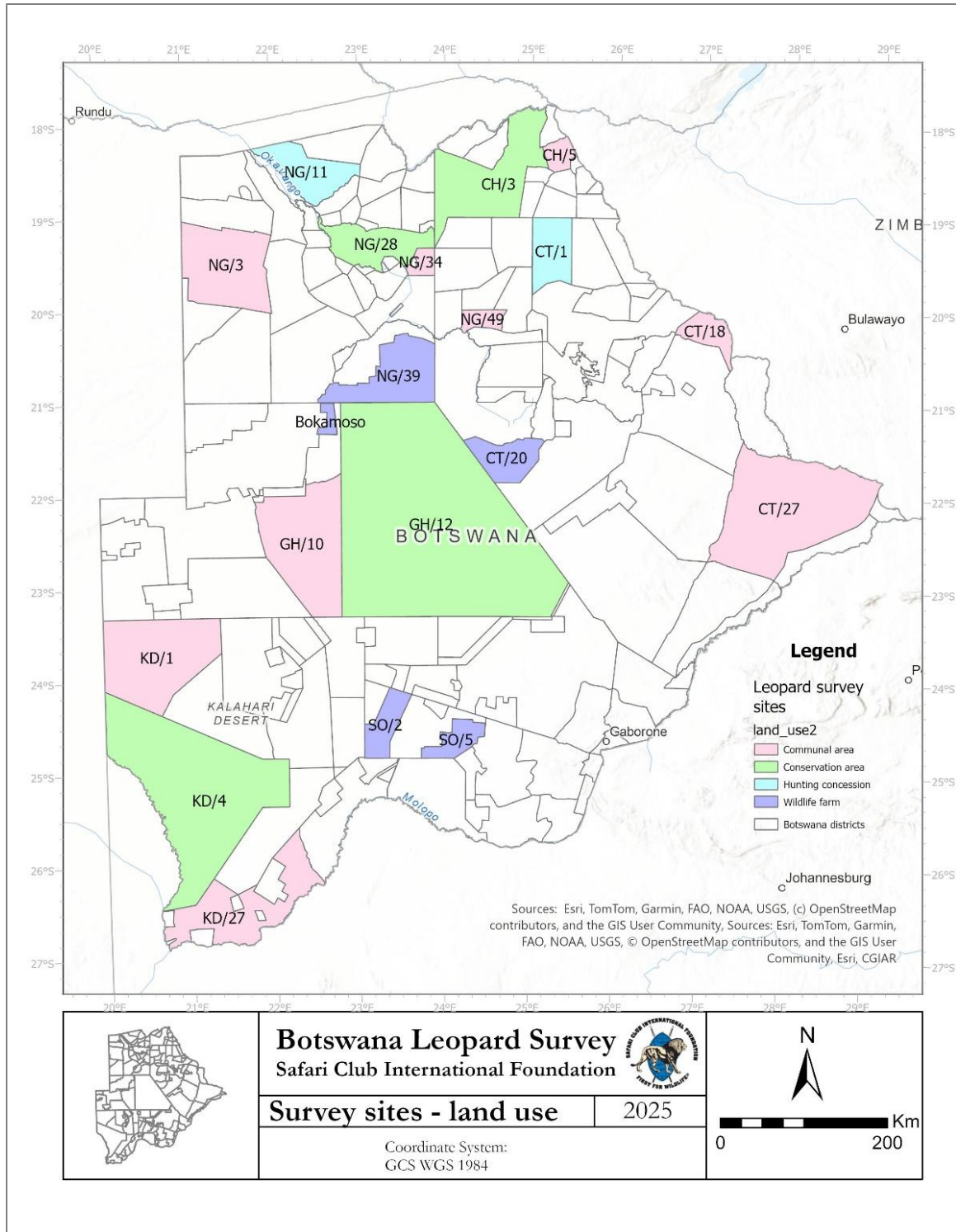


Figure 2. Land use of the focal areas as defined by DWNP. Areas sampled between September 2022 and December 2024.

CONSERVATION AREAS

Approximately 17% of Botswana's land area (98,600 km²) is designated as national parks and game reserves, which are fully protected from consumptive use. National parks are established under the Wildlife Conservation and National Parks Act (Chapter 38) for the propagation, protection, and preservation of wildlife, vegetation, and objects of geological, ethnological, archaeological, historical, or other scientific significance, for the benefit and enjoyment of Botswana's people.

Key protected areas include Chobe National Park and Moremi Game Reserve in the north, Makgadikgadi and Nxai Pans National Parks in the north-central region, the Central Kalahari Game Reserve (CKGR) and Khutse Game Reserve in central Botswana, and the Kgalagadi Transfrontier Park (KTP) in the southwest. Each protected area is managed under its own plan, aligned with the overarching goal of biodiversity conservation. These plans address a broad range of themes, including: zoning for tourism, climate change preparedness, landscape connectivity, fire and habitat management, rare and endangered species conservation, anti-poaching strategies, control of invasive alien species, human-wildlife conflict and problem animal control, research management, ecological monitoring and evaluation, financing for management activities, infrastructure and service provision, tourism regulation and visitor management, as well as community engagement and benefit-sharing.

In addition to parks and reserves, about 20% of Botswana's land (116,000 km²) is designated as Wildlife Management Areas (WMAs). These areas are primarily intended for wildlife use, allowing only activities compatible with conservation, including regulated hunting (Wildlife Conservation and National Parks Act, Botswana, Part III, Sections 15 & 16). WMAs act as buffers between parks and agricultural zones and serve as vital corridors that maintain ecological connectivity between protected areas.

Other important areas for wildlife conservation and connectivity include Botswana's northern forest reserves—Sibuyu, Kazuma, Maikaelelo, Kasane Extension, Kasane, and Chobe—protected under the Forestry Act. These reserves safeguard indigenous hardwood forests and support diverse wildlife populations.

The following protected areas were included among the sampled areas: KD4 (Kgalagadi Transfrontier Park), NG28 (Moremi Game Reserve), CH3 (Chobe National Park), and GH12 (Central Kalahari Game Reserve/CKGR).

COMMUNAL AREAS

Communal areas in Botswana support mixed land uses, primarily livestock husbandry and arable agriculture, and are often situated along the edges of Wildlife Management Areas (WMAs). Among the most valuable land-use practices is Community-Based Natural Resource Management (CBNRM), a government initiative designed to promote the sustainable use and conservation of natural resources by communities living alongside, and often in conflict with wildlife. Under CBNRM, communities are entrusted with the management of local resources, including wildlife, veld products, and cultural assets.

This system provides communities with tangible benefits such as subsistence and commercial use of veld products, handicraft marketing, and employment, education, and training opportunities linked to conservation. Communities adjacent to Controlled Hunting Areas (CHAs) are allocated hunting quotas, which can be used directly or sub-leased to private operators through joint-venture partnerships managed by community-based organizations (CBOs) or trusts. Hunting, the most profitable option under CBNRM, generates substantial revenue, a portion of which is directed into a government conservation fund to support sustainable resource management and biodiversity protection.

Cattle management in communal areas follows two broad systems: commercial and subsistence. Commercial cattle farmers typically adopt strict husbandry practices, maintaining kraals and ranches that reduce losses and increase profitability. These farmers raise cattle primarily for sale to the Botswana Meat Commission (BMC) or supermarkets, contributing significantly to the country's beef export trade, particularly to the European Union. Commercial ranches also play an important role in breeding, beef development, and disease control. Because they occupy large tracts of land, often with undisturbed natural pockets, ranches provide habitat for a range of wildlife species. Examples of cattle ranching areas include NG39, CT20, and SO5 (see Wildlife farms section below).

By contrast, subsistence cattle farming is typically free-range. Cattle are housed in kraals made from thorny branches, which deteriorate over time and require frequent repair. Grazing lands are communal, and cattle roam freely in search of pasture. Due to limited resources, livestock in these systems are generally poorly managed, seldom kraaled, and therefore more vulnerable to predation.

For the leopard survey, the following communal areas and CHAs were included in the sampling design: NG49, NG34, CT18, CT27, NG3, GH10, KD1, KD27, and CH5.

HUNTING CONCESSIONS

Hunting concessions are Wildlife Management Areas (WMAs) designated for commercial resource management. They are predominantly located in northern Botswana, particularly within the Ngamiland, Chobe, and Central (Nata) districts. These areas are leased to private operators, most commonly safari companies, through an open tender process administered by land authorities.

Within concessions, both consumptive uses (e.g., trophy hunting, game capture) and non-consumptive uses (e.g., photographic safaris, ecotourism) are permitted. As with other Controlled Hunting Areas (CHAs), concessions are allocated annual hunting quotas, which are revised each year based on the returns submitted by the concession operators from the previous allocation. Quotas typically include several wildlife species, with allocations determined by the management authority according to management objectives and sustainability criteria.

For the leopard survey, the private hunting concessions included in the sampling design were CT1 and NG11.

WILDLIFE FARMS

Game ranches provide important additional habitat for wildlife in Botswana. Recognized under the Wildlife Conservation and National Parks Act, they play a key role in propagating wildlife for trade and in conserving rare and threatened species. These ranches are managed by private landholders under a “landholder’s privilege” arrangement, which delegates most management responsibilities to the landowner. Government oversight is generally limited to the regulation of protected and partially protected species such as lions, leopards, and eland.

Game ranches are required to maintain up-to-date records of their daily and annual activities to ensure accountability. Management guidelines also mandate game-proof fencing to prevent wildlife from entering or leaving the property. Each year, game ranches are allocated quotas for selected trophy species, including leopard. By utilizing these quotas, ranches generate revenue through sport and trophy hunting, thereby incentivizing private landholders to actively contribute to national conservation efforts.

Like cattle ranches, wildlife farms occupy extensive tracts of land, much of which remains undisturbed and provides habitat for a wide diversity of species.

Wildlife farms included in this survey comprised SO2, NG39, CT20, and Bokamoso Game Farm (BKO). Although SO5 is formally classified by the DWNP as a wildlife farm, it was managed predominantly for cattle production during the survey period and has therefore been considered operationally as a livestock-dominated land use within this analysis.

METHODS

CAMERA TRAP SURVEYS

To estimate leopard density using SECR models, systematic camera-trap surveys were conducted between September 2022 and December 2024. The spatial configuration of each camera-trap array at a sampling site in a focal area was adapted to the logistical constraints and accessibility while adhering as closely as possible to established SECR sampling principles and assumptions. Sampling was designed to achieve representative coverage of the range of available habitats, land-use categories, and levels of human activity across each site, while maintaining sufficient detector density and spatial recaptures to support reliable estimation of SECR model parameters.

Each sampling site in a focal area consisted of a detector array comprising 50–52 camera stations equipped with two opposing Browning Recon Force Edge trail cameras (Browning Trail Cameras, Birmingham, AL, USA). Cameras at each station were positioned 2–3 m. from the potential leopard movement path along roads, game trails, drainage lines, and other natural travel routes or landscape features (Figure 3). This array was expected to maximize leopard detection probability and to obtain simultaneous photographs of both flanks of passing leopards, thereby enabling reliable individual identification.

The survey design followed established SECR sampling principles by balancing broad spatial coverage with detector spacing sufficient to produce spatial recaptures across individual home ranges, thereby supporting reliable estimation of both the detection function and movement parameter. This configuration intended to maximize the probability that individual leopards would be detected at multiple camera stations to generate the spatial encounter histories required for robust estimation of SECR model parameters.

Camera-station spacing was informed by published estimates of leopard home-range size in southern Africa, which indicate substantial spatial requirements and consistently larger home ranges for males than females (Snider et al., 2021; le Roex et al., 2022). Camera stations were spaced approximately 3.5 km apart, based on reported leopard home-range sizes in southern Africa (Snider et al., 2021). Total trap nights for a site were calculated by summing the total number of days that each camera station was active (i.e. at least one camera trap was operational) in the field.

INDIVIDUAL LEOPARD IDENTIFICATION

All photographs containing leopards were compiled into a site-specific image database for individual identification. Photographs captured by camera stations were analyzed using an AI image classification model SpeciesNet (Gadot et al. 2024). Identification was conducted by three independent observers by

comparing all available images from both flanks to ensure consistency and minimize the risk of duplicate identities or misclassification. In some instances, only one flank of a leopard was recorded on camera. For those situations we used the side that resulted in the larger number of leopards and detections recorded for analysis. We excluded juveniles from our dataset due to low recapture rates and only used adult males and females for analyses (Karanth and Nichols 2002). Individuals were identified through systematic comparison of their unique pelage spot patterns, which remain stable throughout life, supplemented by distinctive permanent features such as scars, torn ears, or other natural markings when present (Figure 4).

The sex of each identified leopard was determined using visible morphological characteristics, including the presence of external genitalia, development of the dewlap, degree of frontal bossing, and overall body size, following the criteria described by Swanepoel et al. (2015). When sex could not be assigned with confidence from the available photographs, the individual was classified as having unknown sex. These individuals were excluded from further density estimation analysis but included in the occupancy modeling process.



Figure 3. Details of trail camera and sampling station (red arrows) used in the leopard survey. SCIF Botswana Leopard Survey (September 2022 – December 2024).

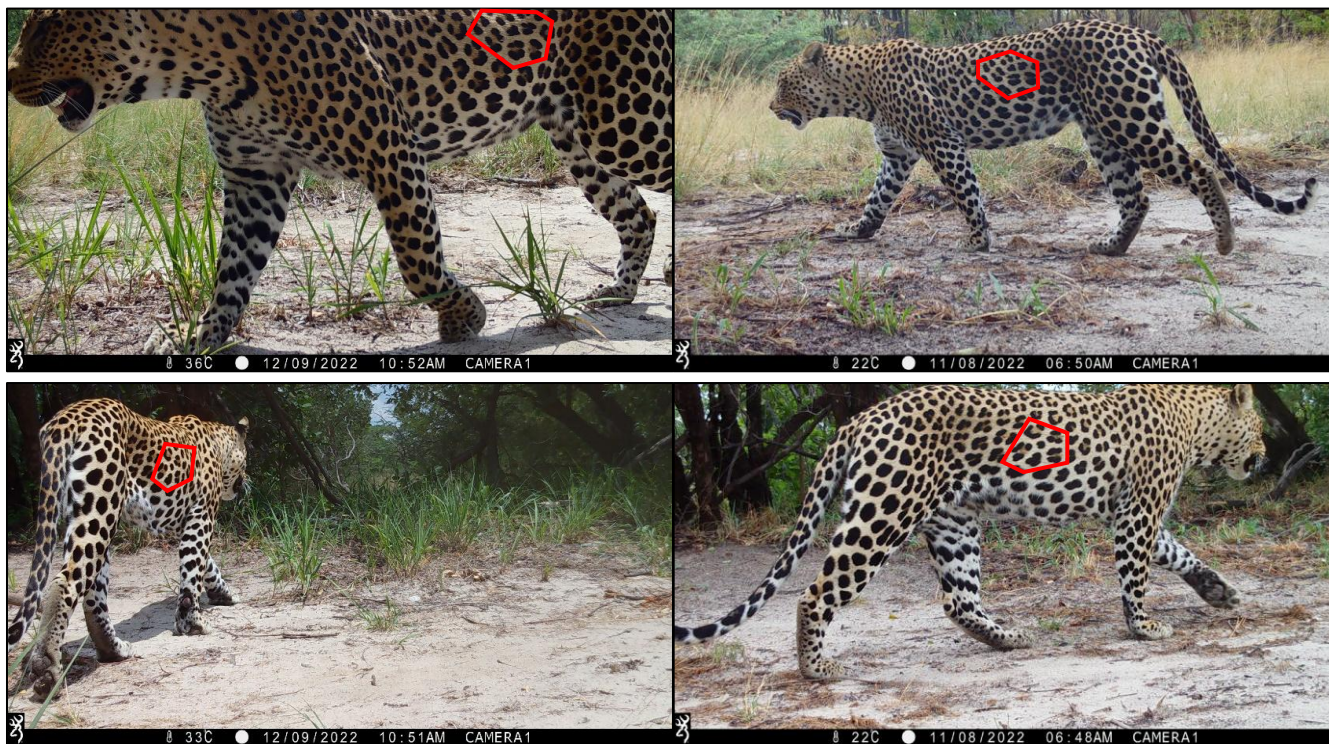


Figure 4. Individual leopards were identified by means of their pelage characteristics. Red polygons show spots used in the identification of male leopard detected in CT1.

LANDSCAPE COVARIATES

We selected landscape covariates based on established aspects of leopard ecology and previous landscape-scale analyses of leopard and other large-carnivore density (e.g., Loveridge et al. 2022). Covariates were selected to characterize environmental and anthropogenic features hypothesized to influence spatial variation in leopard density, including vegetation productivity and structure, land-cover composition and heterogeneity, terrain, rainfall, proximity to surface water, and human development. Where appropriate, covariates were summarized within circular buffers of 5, 10, 15, and 20 km radius centered on each camera station to evaluate the spatial scale at which each variable was most strongly associated with leopard density.

Normalized Difference Vegetation Index (NDVI)

Vegetation productivity was characterized using the Normalized Difference Vegetation Index (NDVI) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation-index product (Didan 2021). MODIS vegetation indices are produced at 16-day intervals at a spatial resolution of 250 m. NDVI provides an index photosynthetically active vegetation and was used as an indirect surrogate for spatial variation in prey abundance and availability through its relationship with primary productivity and the resources available to herbivore populations. Prey availability is an important bottom-up determinant of leopard abundance and density, and vegetation productivity can influence both the abundance and spatial distribution of ungulate prey (Searle et al. 2021). NDVI has consequently been used in leopard studies as an indicator of vegetation productivity and as a proxy for ecological processes influencing prey availability and catchability (Smyth et al. 2025).

Because vegetation productivity varies temporally, we selected NDVI data corresponding to the timing of camera-trap sampling at each survey site. This approach provided a measure of vegetation productivity representative of conditions during each respective survey rather than relying on a single static vegetation layer for all sampling periods. NDVI values were summarized by calculating the average within the 5-, 10-, 15-, and 20-km candidate buffers surrounding each camera station.

Land Cover and Landscape Heterogeneity

Land-cover composition was quantified using the European Space Agency (ESA) WorldCover 2021 product at 10-m spatial resolution (Zanaga et al. 2022). We calculated the proportional representation of relevant land-cover classes within each candidate buffer surrounding camera stations. Land-cover composition was included to characterize broad differences in habitat structure and resource distribution that could influence leopard space use, prey communities, and ultimately leopard density.

We additionally calculated a measure of landscape heterogeneity (Shannon Heterogeneity Diversity Index, SHDI) from the distribution of land-cover classes within each candidate buffer using the *landscapemetrics* R package (Hesselbarth et al. 2019). Landscape heterogeneity was included to represent variation in the composition and complexity of habitat surrounding camera locations, because heterogeneous landscapes may provide a greater diversity of habitat conditions, prey resources, and stalking or refuge opportunities for leopards. SHDI was averaged within the 5-, 10-, 15-, and 20-km candidate buffers surrounding each camera station.

Distance to Built-up Areas

Potential human influence was represented in part by the Euclidean distance from each camera station to the nearest area classified as built-up in the ESA WorldCover 2021 dataset (Zanaga et al. 2022). Distance to built-up areas was included as an indicator of proximity to human development and associated anthropogenic disturbance. Unlike covariates describing conditions across the surrounding landscape, distance to built-up areas was calculated as a Euclidean point-based distance from each camera station and was therefore not summarized within spatial buffers.

Rainfall

Rainfall was characterized using the Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS), which provides precipitation estimates at approximately 0.05° spatial resolution (Funk et al. 2015). Rainfall can influence primary productivity, surface-water availability, and the abundance and distribution of herbivore populations, thereby potentially affecting the spatial distribution and density of large carnivores. Cumulative rainfall for 2023–2024 was calculated and mean cumulative rainfall was summarized within the 5-, 10-, 15-, and 20-km candidate buffers surrounding each camera station.

Elevation

Elevation was derived from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), developed by the U.S. Geological Survey and the National Geospatial-Intelligence Agency (Danielson and Gesch 2011). Elevation can reflect broad environmental gradients associated with vegetation communities, climate, hydrology, human accessibility, and prey distribution. Mean elevation was calculated within each candidate spatial buffer surrounding camera stations.

Slope

Slope was derived from the GMTED2010 elevation surface (Danielson and Gesch 2011) and was included to characterize variation in terrain steepness. Slope can influence accessibility, vegetation structure, prey

distribution, and the movement and hunting behavior of leopards. Mean slope was summarized within each candidate spatial buffer.

Terrain Ruggedness

Terrain ruggedness was derived from GMTED2010 and quantified using a terrain ruggedness index representing local variation in elevation. Rugged terrain may influence leopard density by providing cover and stalking opportunities, affecting prey vulnerability and distribution, and potentially reducing accessibility to people. Terrain ruggedness and related topographic metrics have therefore been identified as important predictors of leopard habitat use and density in several landscapes. Mean-terrain ruggedness was averaged within each candidate spatial buffer.

Tree Cover

Vegetation structure was further characterized using MODIS Vegetation Continuous Fields (VCF), which provides annual estimates of percentage tree cover and other vegetation-cover components at approximately 250-m spatial resolution (DiMiceli et al. 2021). Percentage tree cover was included as a measure of woody vegetation structure because vegetation cover can influence concealment, hunting opportunities, resting and refuge habitat, and the distribution of leopard prey. Mean percentage tree cover was calculated within each candidate spatial buffer.

Distance to Rivers and Streams

Proximity to riverine environments was represented by the Euclidean distance from each camera station to the nearest mapped river or stream using the HydroRIVERS dataset derived from HydroSHEDS (Lehner and Grill 2013). Although leopards are not strictly dependent on permanent surface water, riverine and riparian environments may provide important habitat features by supporting relatively high prey availability, dense vegetation cover, stalking opportunities, and movement corridors. Leopards have been reported to preferentially use riverine habitats in some African landscapes, potentially because these areas concentrate prey and provide vegetation structure that facilitates concealment and prey capture (Bailey 1993; Balme et al. 2007; Swanepoel et al. 2013). We therefore included distance to rivers as a candidate predictor of spatial variation in leopard density, hypothesizing that leopard density would increase with proximity to riverine environments where these habitats provide favorable prey and hunting conditions.

Spatial Coordinates

Projected spatial coordinates were included as candidate covariates to characterize broad-scale geographic variation in leopard density that might not be fully explained by the measured environmental and

anthropogenic variables. Including spatial coordinates allowed us to evaluate whether systematic geographic gradients in density remained after accounting for the candidate landscape covariates.

Covariate Screening and Standardization

Prior to model fitting, we evaluated collinearity among candidate covariates using pairwise Pearson correlation coefficients at each spatial scale. Covariate pairs with $|r| \geq 0.70$ were considered strongly correlated and were not included together in the same multivariable model (Zuur et al. 2010, Dormann et al. 2013). Continuous covariates were standardized by centering on their mean and scaling by their standard deviation prior to model fitting. Standardization placed covariates on comparable scales, improved numerical stability, and facilitated comparison and interpretation of model coefficients.

Selection of Spatial Scale

To identify the spatial scale at which each buffered landscape covariate was most strongly associated with leopard density, we fitted separate univariate density models for each covariate at candidate buffer radii of 5, 10, 15, and 20 km. Models representing alternative spatial scales for the same covariate were compared using Akaike's Information Criterion corrected for small sample size (AICc; Burnham and Anderson 2002). The spatial scale associated with the most strongly supported model was retained as the scale of effect for that covariate in subsequent multivariable leopard-density modeling (McGarigal et al. 2016, Loveridge et al. 2022). Point-based distance covariates and projected spatial coordinates were not subjected to buffer-scale selection because their values were defined at the camera-station location.

DENSITY ESTIMATION¹

Estimating leopard density and predicting national distribution

We used camera-trap data to estimate leopard density at each survey site and to examine how leopard density varied across Botswana. Because individual leopards can be identified from their unique coat patterns, photographs from the camera traps allowed us to determine which animals were detected, where they were detected, and how often they were photographed.

To estimate density, we used spatially explicit capture–recapture (SECR) methods. These methods are specifically designed for studies in which individually identifiable animals are detected at known camera locations. SECR models use both the number of times an animal is detected and the spatial pattern of those detections. For example, a leopard photographed at several neighboring camera stations provides

¹ For a technical description of the density modeling framework refer to Appendix A.

information about the area over which that animal is moving. This information helps estimate the likely location of its home-range center and the probability that it will be detected by cameras at different distances from that center.

An important advantage of SECR is that it estimates leopard density directly while accounting for animals that may live partly outside the camera-trap array but still enter the surveyed area and are photographed. This is especially important for leopards because individuals can have large home ranges and may move across the boundaries of a survey site.

We first analyzed the data using the R statistical package *secr*. Information from all survey sites was analyzed within a common framework so that density could be estimated consistently across Botswana. The area considered around each camera array was extended sufficiently beyond the outermost cameras to include leopards whose home-range centers may have occurred outside the surveyed area but that still had a realistic chance of being detected.

We also tested several factors that could influence how likely a leopard was to be photographed. Male and female leopards differ in their movement patterns and home-range sizes, so we tested whether detection and movement differed between the sexes. We also tested whether a leopard's probability of being photographed at a particular camera changed after it had previously been detected there.

Not all differences among individual leopards can be measured directly. Some animals may move differently because they are dispersing, breeding, territorial, or otherwise behaving differently from other individuals. We therefore also tested models that allowed for additional, unmeasured differences among animals in their movement and detectability. Accounting for these sources of variation helps reduce the risk that differences in animal behavior are incorrectly interpreted as differences in population density.

Several alternative SECR models were compared, representing different explanations for variation in density and detection. The models were evaluated using standard statistical model-selection procedures, and the model receiving the strongest support from the data was used to estimate leopard density at each survey site. These estimates, together with their measures of uncertainty, provide the principal site-specific density estimates presented in this report.

We also analyzed the camera-trap data using SPACECAP, a second spatial capture–recapture method. Whereas the *secr* analysis was primarily used to estimate overall density for each survey site, SPACECAP allowed us to examine how leopard density was distributed spatially within individual survey areas. The survey landscape was divided into 1 × 1 km grid cells, and the model estimated the relative distribution of leopard activity centers across those cells.

Using two complementary analytical approaches provided both site-level density estimates and more detailed information about how leopard density varied within the surveyed landscapes. The spatial estimates from SPACECAP were then linked to environmental information at the camera locations.

Identifying landscape factors associated with leopard density

The next step was to determine which landscape characteristics were most strongly associated with variation in leopard density. We compared the spatial leopard-density estimates with environmental and human-related variables such as vegetation productivity, land cover, rainfall, proximity to developed areas, and geographic location.

For each environmental variable, we first determined the spatial scale at which it was most strongly related to leopard density. We also removed variables that were highly correlated with one another so that the final models did not contain several predictors representing essentially the same landscape characteristic.

We then compared a series of statistical models representing different combinations of environmental variables. These models allowed us to evaluate alternative explanations for why leopard density was higher in some landscapes and lower in others. Models were compared using standard statistical criteria that balance how well each model fits the observed data against the number of variables required to explain the pattern. The best-supported landscape model was then applied across Botswana using national environmental map layers. This produced a continuous predictive map showing how leopard density would be expected to vary across the country based on the relationships observed at the surveyed sites.

Estimating national abundance and uncertainty

The national density map was also used to estimate the number of leopards potentially occurring across the modeled area. Predicted density in each map cell was converted to the expected number of leopards and then summed across the landscape.

Because statistical models contain uncertainty, we did not rely on a single set of model estimates. Instead, we repeated the national prediction 1,000 times while allowing the estimated relationships between leopard density and the environmental variables to vary within their statistical uncertainty. This produced 1,000 plausible national abundance estimates. The median estimate represents the expected national abundance from the model, while the lower and upper bounds describe the range of values supported by uncertainty in the fitted landscape model. These bounds should therefore be interpreted as an indication of uncertainty around the national prediction rather than as exact limits on the true number of leopards in Botswana.

The site-specific SECR estimates remain the most direct measures of leopard density for the surveyed areas. The national predictive map is intended to complement these estimates by showing broader patterns in

where leopard density is expected to be relatively high or low across Botswana. It should therefore be used primarily for national-scale planning, identifying priority areas, highlighting information gaps, and guiding future monitoring rather than as a replacement for direct site-specific density estimates.

OCCUPANCY MODEL²

Estimating leopard occupancy across Botswana

In addition to estimating leopard density, we evaluated leopard occupancy, which describes the extent to which leopards use the landscape. Occupancy is expressed as the probability of occupancy, or the probability that leopards are present in, or use, a particular area during the survey period. Unlike density, occupancy does not estimate how many leopards occur in an area; rather, it provides a measure of how widely leopards are distributed across the landscape and identifies areas with higher or lower probabilities of leopard use.

Occupancy analyses also account for imperfect detection, recognizing that a leopard may use an area without being photographed by a camera during a particular sampling period. Detection probability is defined as the probability of detecting a leopard when it is present in, or using, the area being surveyed. By accounting for the possibility that leopards may be present but go undetected, occupancy models provide a more reliable estimate of leopard distribution than simply considering whether a leopard was photographed at each camera station.

We estimated occupancy using repeated camera-trap observations. For each camera station, the survey period was divided into 7-day sampling periods, and each week was recorded according to whether a leopard was detected or not detected. This produced a detection history for every camera station across the survey period. An important feature of occupancy modeling is that it recognizes that failing to photograph a leopard does not necessarily mean that leopards were absent from that location. A leopard may have been present but simply not passed close enough to a camera during a particular week. The analysis therefore estimated two things separately: the probability that leopards used a location and the probability of detecting a leopard with cameras when the species was present.

Because weather and environmental conditions can influence whether leopards move past cameras or whether cameras record them, we first examined factors that could affect detection. These included weekly rainfall, vegetation greenness (NDVI), and minimum and maximum temperatures. We compared alternative

² For a technical description of the occupancy modeling framework refer to Appendix B.

models to determine which combination of these factors best explained variation in the probability of detecting leopards.

Once the most appropriate detection model had been identified, we examined which landscape characteristics were associated with leopard occupancy. For consistency with the national density analysis, we evaluated the same landscape variables and spatial scales that were identified as important in the density modeling. This allowed us to assess whether environmental conditions associated with higher or lower leopard density were also related to the probability that leopards used different parts of Botswana.

We compared a series of alternative occupancy models representing different combinations of landscape variables. Models were evaluated using standard statistical criteria that balance how well each model explained the observed data against the number of variables included. Rather than relying on a single model when several models received substantial support from the data, we combined information from the set of well-supported models. Models contributing 90% of the cumulative statistical support were included in this model-averaging process. This approach reduces reliance on any one particular model and incorporates uncertainty about which combination of landscape variables best explains leopard occupancy.

The resulting relationships were then applied to national environmental map layers to predict leopard occupancy across Botswana. The country was divided into 1 × 1 km grid cells, and each cell was assigned a predicted probability of leopard occupancy ranging from 0 to 1. Values closer to 1 indicate areas with a higher predicted probability of leopard use, whereas values closer to 0 indicate areas where leopard use is predicted to be less likely.

The final occupancy map therefore provides a national-scale representation of the relative probability of leopard occurrence or use across Botswana. This information complements the density analysis. Whereas the density map indicates where greater or fewer numbers of leopards are expected, the occupancy map provides information on how broadly leopards are distributed and can help identify areas of likely occurrence, potential connectivity between populations, and areas where additional monitoring may be warranted.

Finally, we evaluated how well the occupancy model distinguished between camera stations where leopards were detected and stations where they were not detected. This provided an indication of the model's ability to reproduce patterns observed within the surveyed areas. Because this evaluation used the same survey data used to develop the model, it should be interpreted as a measure of model fit to the available data rather than as an independent test of predictive performance in unsurveyed areas.

RESULTS

SAMPLING AND LEOPARD IDENTIFICATION³

Between October 2022 and December 2024, we conducted camera-trap surveys at 20 independent sampling sites across Botswana, encompassing approximately 21,925 km². A total of 1,014 camera stations were deployed, with most survey sites containing between 50 and 52 stations. Sampling periods varied among survey sites, with camera traps surveys conducted for a minimum of 60 days at some sites and extended for up to 160 days at others, resulting in 83,347 trap nights of sampling effort.

Field teams established standardized camera-trap arrays using a common survey design, while adapting the exact placement of individual stations to local landscape and access conditions. Stations were positioned to maintain appropriate spacing across the survey area while also increasing the likelihood of photographing leopards by placing cameras along roads, trails, drainage lines, and other features commonly used by wildlife. At some sites, difficult terrain, limited road access, seasonal flooding, or other logistical constraints prevented the establishment of an ideal sampling grid. In these cases, station locations were adjusted as necessary while maintaining the overall objectives of achieving broad spatial coverage and obtaining sufficient leopard detections for analysis.

The surveys produced approximately 2.74 million wildlife detections, including 1,424 independent leopard detections were retained. Examination of the unique coat patterns visible in these photographs allowed us to identify 434 individual adult leopards, comprising 246 females, 170 males, and 18 individuals whose sex could not be determined (Table 1). The large number of individually recognizable leopards, together with repeated detections of many individuals at different camera stations, provided the information needed to estimate leopard density using spatially explicit capture–recapture methods.

Repeated detections of the same individuals are particularly important for density estimation because they provide information on how individual leopards move. Leopards were redetected at 19 of the 20 survey sites. At the remaining site, only a single leopard was detected, and no individual was subsequently redetected. Because reliable spatial capture–recapture density estimation requires sufficient detections and redetections, this site was excluded from the site-level density analysis. The detection nevertheless provided valid information on leopard occurrence, so the site was retained in the occupancy analysis, which evaluates the probability that leopards use different parts of the landscape.

³ For a discussion about the length of the sampling periods in this study and the validity of the assumption of population closure see Appendix C

LEOPARD DENSITY AND SPATIAL PATTERNS ACROSS BOTSWANA⁴

Leopard density varied substantially across Botswana, with differences among survey sites, land-use types, geographic areas, and between males and females (Figure 5; Table 2; see Appendix 1 for detailed model results). For each survey site, we also calculated measures of uncertainty to show how precise each density estimate was. These measures included standard error, 95% confidence interval, and coefficient of variation (CV). Together, these statistics indicate how much confidence can be placed in each estimate and help distinguish relatively precise estimates from those that should be interpreted more cautiously.

The highest estimated leopard density occurred in NG28 (Moremi), with 2.74 leopards per 100 km², while the lowest occurred in CT27, with 0.15 leopards per 100 km². At site SO5, only a single male leopard was detected during the survey. This was insufficient to produce a reliable density estimate, so SO5 was excluded from the analyses examining factors associated with leopard density. However, the detection from SO5 remained useful for determining leopard distribution and the site was therefore retained in the occupancy analysis.

We examined a range of environmental and geographic factors to determine which best explained differences in leopard density across Botswana. The strongest predictors were rainfall and vegetation productivity measured across a 20-km surrounding area, landscape diversity measured across a 5-km area, and geographic position within Botswana. These variables were subsequently used to examine broad-scale patterns in leopard density and occupancy.

The analysis showed that individual leopards differed in how often they were photographed and in how widely they appeared to move across the camera array. To account for these differences, the statistical model grouped leopards into two detection groups based on their observed camera-trap patterns. Leopards in one group were more likely to be photographed when they passed through the area monitored by a camera station, whereas leopards in the other group were less likely to be photographed during a similar opportunity for detection but tended to be detected over larger areas.

These groups should not be interpreted as two distinct types of leopards. Instead, they are a statistical way of accounting for natural differences among individuals that were not measured directly. Ecologically, these differences could reflect variation in home-range size, territorial behavior, breeding activity, dispersal, or how frequently individual leopards use roads, trails, and other features where cameras were placed. Accounting for this variation helps reduce bias and improves the reliability of the resulting leopard density estimates.

⁴ For a technical description of this section see Appendix D.

Movement patterns also differed between males and females. Female movement estimates ranged from approximately 2.0 to 4.7 km, depending on the individual detection group, whereas corresponding estimates for males ranged from approximately 3.4 to 7.9 km. Males therefore tended to range over larger areas than females, consistent with the general spatial ecology of leopards. Estimated male density was also lower than female density across survey sites, reflecting the larger home ranges and lower spatial density typically expected for male leopards.

The national density analysis was based on 943 camera stations across 19 survey sites after SO5 was excluded. The best-supported model indicated that leopard density was associated with several broad environmental patterns. Density tended to be lower in areas receiving greater rainfall, but higher in areas with greener and more productive vegetation, greater landscape diversity, and toward the northern parts of Botswana. These relationships likely reflect broad differences in habitat productivity, vegetation structure, prey availability, water distribution, land use, and other ecological conditions influencing where leopards can occur at higher densities.

Using these relationships, we produced a national map predicting leopard density at a resolution of 1 km² across Botswana (Figure 6). Predicted density varied substantially across the country, ranging from approximately 0.2 to 7.5 leopards per 100 km², with an average predicted density of approximately 1.1 leopards per 100 km².

When these predicted densities were applied across approximately 579,075 km² of terrestrial habitat in Botswana, the model produced a median national population estimate of approximately 6,262 leopards, with a 95% confidence interval of 5,676–6,849 leopards. This national estimate represents a model-based prediction derived from the relationships observed at the surveyed sites and should therefore be interpreted together with the site-specific density estimates, their uncertainty, and the geographic coverage of the surveys.

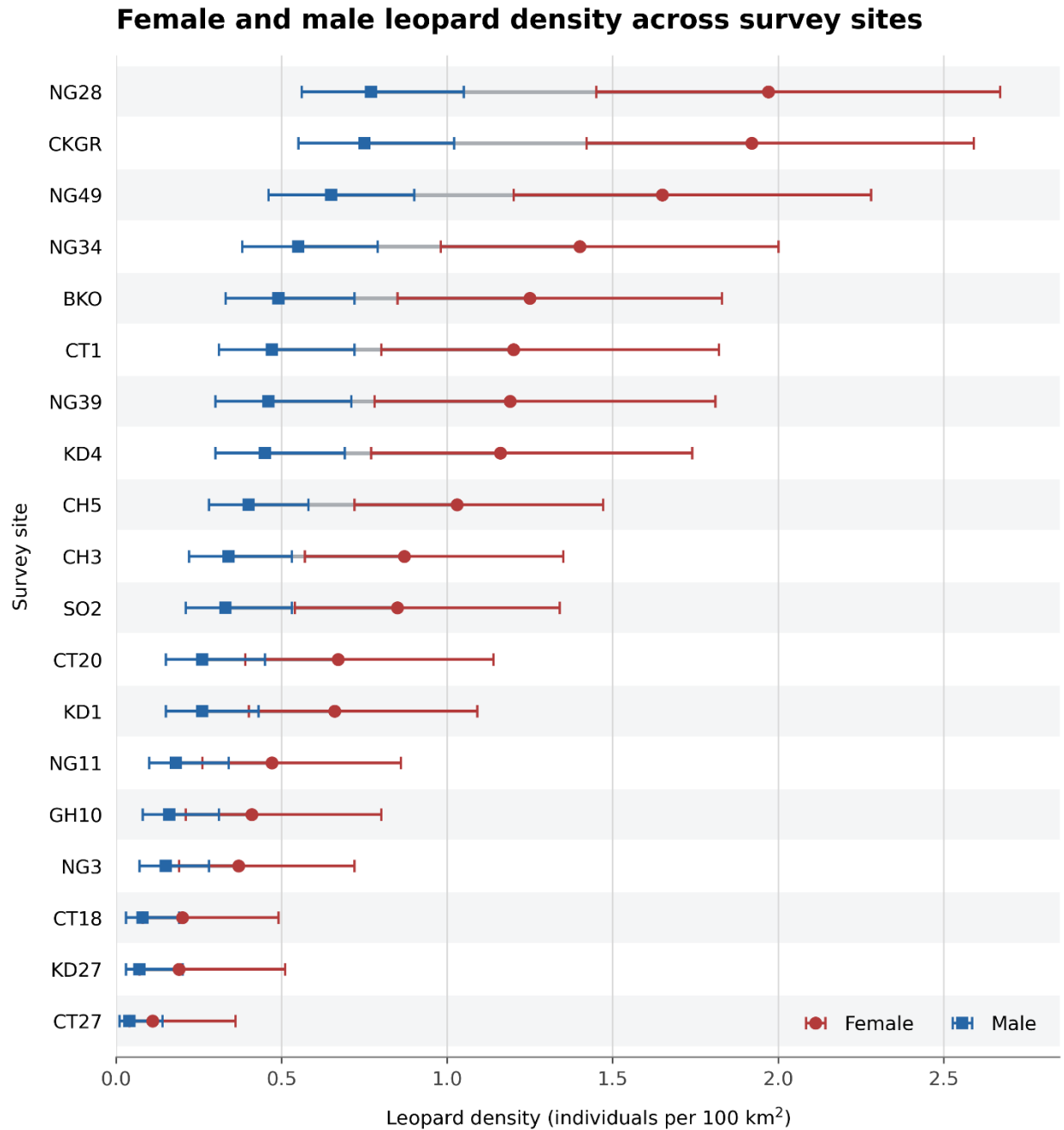


Figure 5. Variation of leopard densities by sex and sampling area estimated using tail camera data and SECR modeling. SCIF Botswana Leopard Survey (September 2022 – December 2024). Points show density estimates; whiskers show 95% confidence intervals; grey lines connect sexes within sites.

Table 1. Trapping effort summary for leopard camera-trapping surveys conducted at 20 sites in Botswana. SCIF Botswana Leopard Survey (September 2022-December 2024). ¹Camera station sampling area (km²) was calculated using a minimum convex polygon around all stations at each site.

Sampling site	No. of camera stations	¹ Camera station sampling area (km ²)	Detections	Leopards identified	Females	Males	Unknown	Sampling period (days)	Trap nights
BKO	52	788	119	29	16	12	1	90	4,680
CH3	50	1440	52	22	14	8	0	70	3,500
CH5	50	1456	87	33	19	14	0	140	7,000
CKGR	52	1320	211	56	22	27	7	89	4,539
CT1	52	738	76	24	15	9	0	65	3,380
CT18	52	802	27	5	3	2	0	150	7,800
CT20	51	835	41	16	10	4	2	70	3,570
CT27	51	842	14	5	1	2	2	160	8,160
GH10	50	943	35	9	5	4	0	65	3,250
KD1	50	1378	37	19	11	5	3	60	3,000
KD4	50	1141	70	25	14	11	0	60	3,000
KD27	50	981	8	4	3	1	0	60	3,000
NG3	50	2605	17	9	6	3	0	60	3,000
NG11	50	1265	20	11	7	4	0	60	3,000
NG28	50	985	147	46	30	16	0	75	3,750
NG34	51	854	76	34	20	12	2	85	4,335
NG39	52	682	96	23	15	8	0	70	3,640
NG49	51	923	214	43	22	20	1	93	4,743
SO2	50	1255	76	20	13	7	0	60	3,000
SO5	50	692	1	1	0	1	0	60	3,000

Table 2. Estimated leopard density (leopards/100 km²) for 19 sampled sites in Botswana between September 2022-December 2024. SO5 had a single leopard detection – no density estimate was produced for that site.

	Total	Females					Males				
Site	D_{total}	D_{female}	SE_{female}	LCL_{female}	UCL_{female}	CV_{female}	D_{male}	SE_{male}	LCL_{male}	UCL_{male}	CV_{male}
BKO	1.74	1.25	0.25	0.85	1.83	0.2	0.49	0.10	0.33	0.72	0.20
CH3	1.21	0.87	0.19	0.57	1.35	0.22	0.34	0.08	0.22	0.53	0.23
CH5	1.43	1.03	0.19	0.72	1.47	0.18	0.40	0.08	0.28	0.58	0.19
CKGR	2.67	1.92	0.29	1.42	2.59	0.15	0.75	0.12	0.55	1.02	0.16
CT1	1.67	1.20	0.26	0.80	1.82	0.21	0.47	0.10	0.31	0.72	0.22
CT18	0.28	0.20	0.10	0.08	0.49	0.47	0.08	0.04	0.03	0.19	0.48
CT20	0.93	0.67	0.19	0.39	1.14	0.28	0.26	0.07	0.15	0.45	0.28
CT27	0.15	0.11	0.07	0.04	0.36	0.63	0.04	0.03	0.01	0.14	0.63
GH10	0.57	0.41	0.14	0.21	0.80	0.35	0.16	0.06	0.08	0.31	0.35
KD1	0.92	0.66	0.17	0.40	1.09	0.26	0.26	0.07	0.15	0.43	0.26
KD27	0.26	0.19	0.10	0.07	0.51	0.54	0.07	0.04	0.03	0.20	0.54
KD4	1.61	1.16	0.24	0.77	1.74	0.21	0.45	0.10	0.30	0.69	0.21
NG11	0.65	0.47	0.15	0.26	0.86	0.31	0.18	0.06	0.10	0.34	0.32
NG28	2.74	1.97	0.31	1.45	2.67	0.16	0.77	0.13	0.56	1.05	0.16
NG3	0.52	0.37	0.13	0.19	0.72	0.35	0.15	0.05	0.07	0.28	0.35
NG34	1.95	1.40	0.26	0.98	2.00	0.19	0.55	0.10	0.38	0.79	0.19
NG39	1.65	1.19	0.26	0.78	1.81	0.22	0.46	0.10	0.30	0.71	0.22
NG49	2.30	1.65	0.27	1.20	2.28	0.16	0.65	0.11	0.46	0.90	0.17
SO2	1.18	0.85	0.20	0.54	1.34	0.23	0.33	0.08	0.21	0.53	0.24

D: density estimate, SE: standard error, LCL: 95% confidence interval lower limit, UCL: 95% confidence interval upper limit. CV: coefficient of variation.

OCCUPANCY⁵

Leopards were detected at 381 of the 947 camera stations, meaning that approximately 40% of surveyed camera locations recorded at least one leopard during the study. This simple proportion does not account for the fact that leopards may have been present at some locations without being photographed, so the occupancy analysis was used to estimate the probability that an area was used by leopards while accounting for imperfect detection.

The probability of photographing a leopard varied with short-term weather and vegetation conditions. Leopards were generally less likely to be detected during wetter weeks, and detection also varied with minimum and maximum temperatures. In contrast, the probability of detecting a leopard increased during weeks when vegetation was greener, as measured by NDVI. These relationships indicate that environmental conditions can influence how frequently leopards move past camera stations or use roads, trails, and other locations where cameras were placed.

At the broader landscape scale, leopard occupancy was most strongly associated with rainfall, landscape diversity, and geographic location within Botswana. Occupancy tended to be lower in areas with higher rainfall, but higher in areas containing a greater diversity of habitat types and toward the northern parts of the country. Greener vegetation, as measured by NDVI, showed only a weak relationship with occupancy and was therefore less important in explaining where leopards occurred.

The best-supported occupancy model included rainfall, landscape diversity measured within 5 km, and geographic position. However, several alternative models also received support, indicating some uncertainty about the exact combination of factors influencing leopard distribution. Rather than relying on a single model, predictions were therefore averaged across the five best-supported models, which together accounted for approximately 92% of the overall model support.

The resulting national occupancy map (Figure 7) showed substantial variation in the predicted probability of leopard occurrence across Botswana. Predicted occupancy ranged from approximately 0.10 to 0.73, with an average of 0.41 across the country. In practical terms, this means that some areas were predicted to have a relatively low probability of leopard use, whereas others had a much higher likelihood of supporting leopards.

⁵ For a technical version of this section see Appendix E.

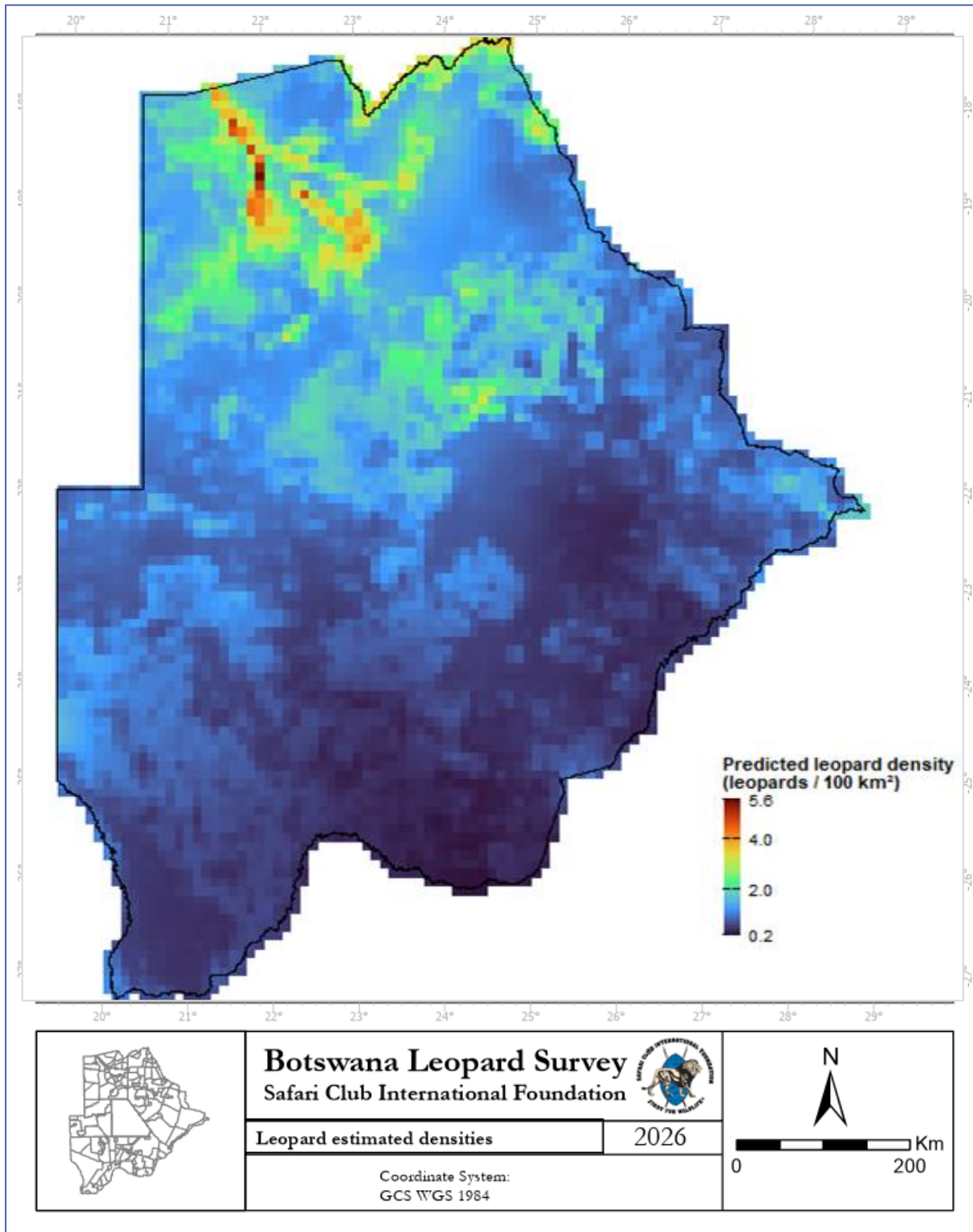


Figure 6. National-scale predicted leopard density surface derived by applying the top-supported GLM to national raster layers representing the selected environmental covariates and their scales of effect.

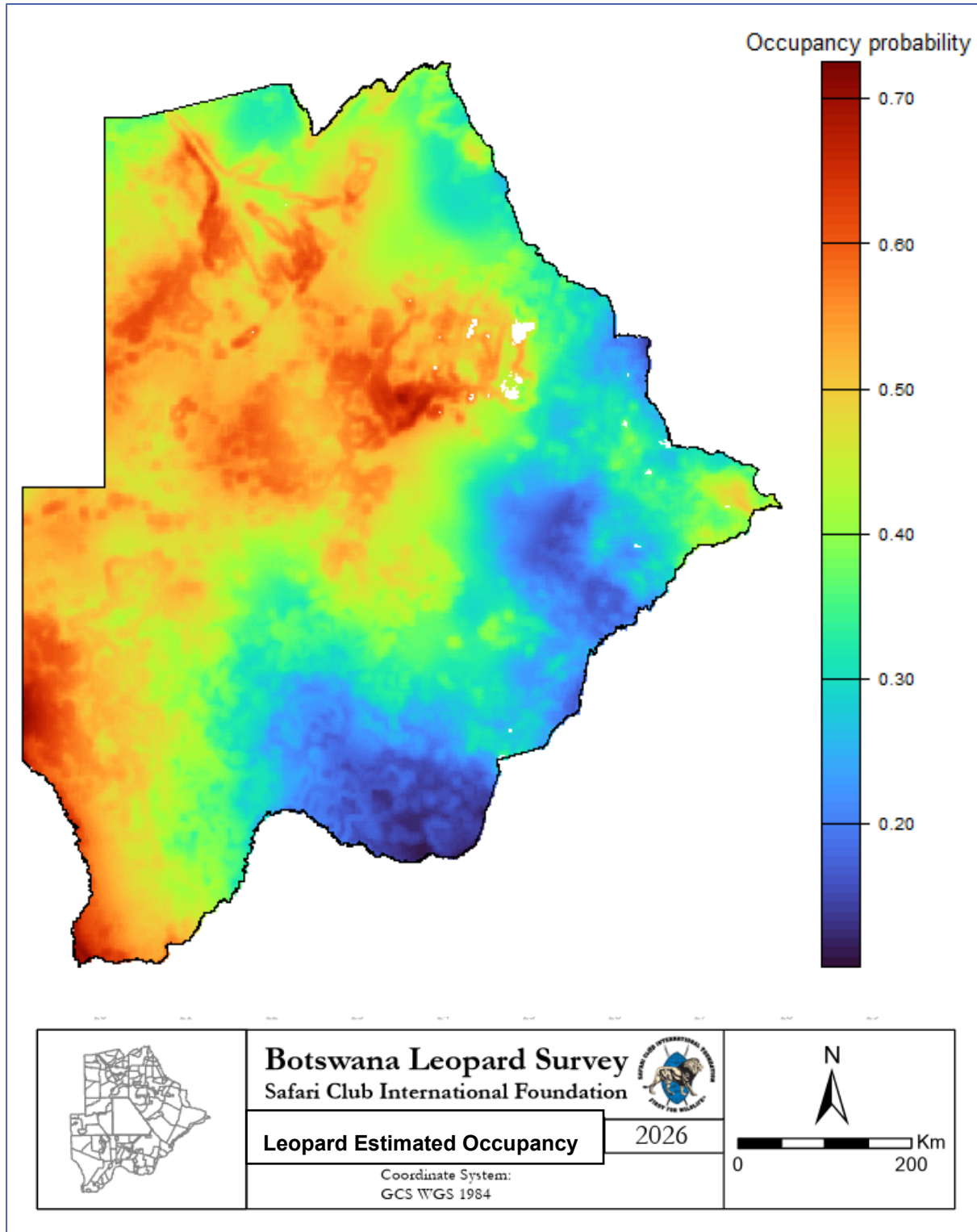


Figure 7. Leopard distribution patterns across Botswana. Grid shading (with darker red color indicating higher probability of occupancy) shows the variation in occupancy patterns based on model average estimates.

SITE-SPECIFIC LEOPARD SURVEY PROFILES

Detailed results for each leopard survey site are presented in the following sections. To facilitate interpretation, reference, and distribution to managers and other stakeholders, the results for each site are organized as a standardized three-page site profile. This format allows information for an individual survey area to be reviewed independently while maintaining consistency across all sites included in the national assessment.

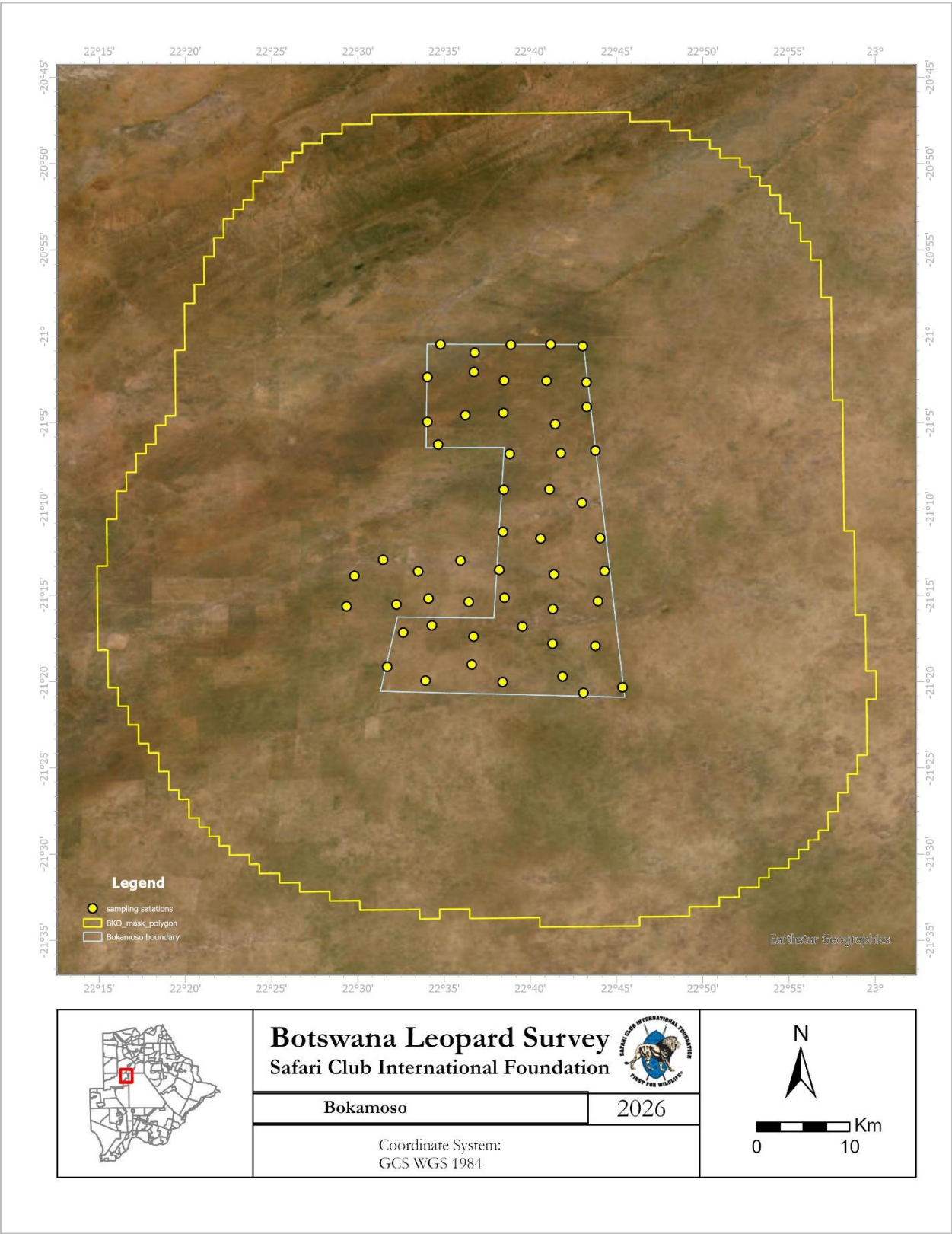
The first page provides a map of the survey area showing the spatial configuration and location of camera-trap sampling stations and a polygon representing the SECR state-space area. This SECR state-space area represents the area defined by the habitat mask and buffer around the camera array and is used in the density estimation. This map provides geographic context for the survey and illustrates the extent and distribution of sampling effort within the study area.

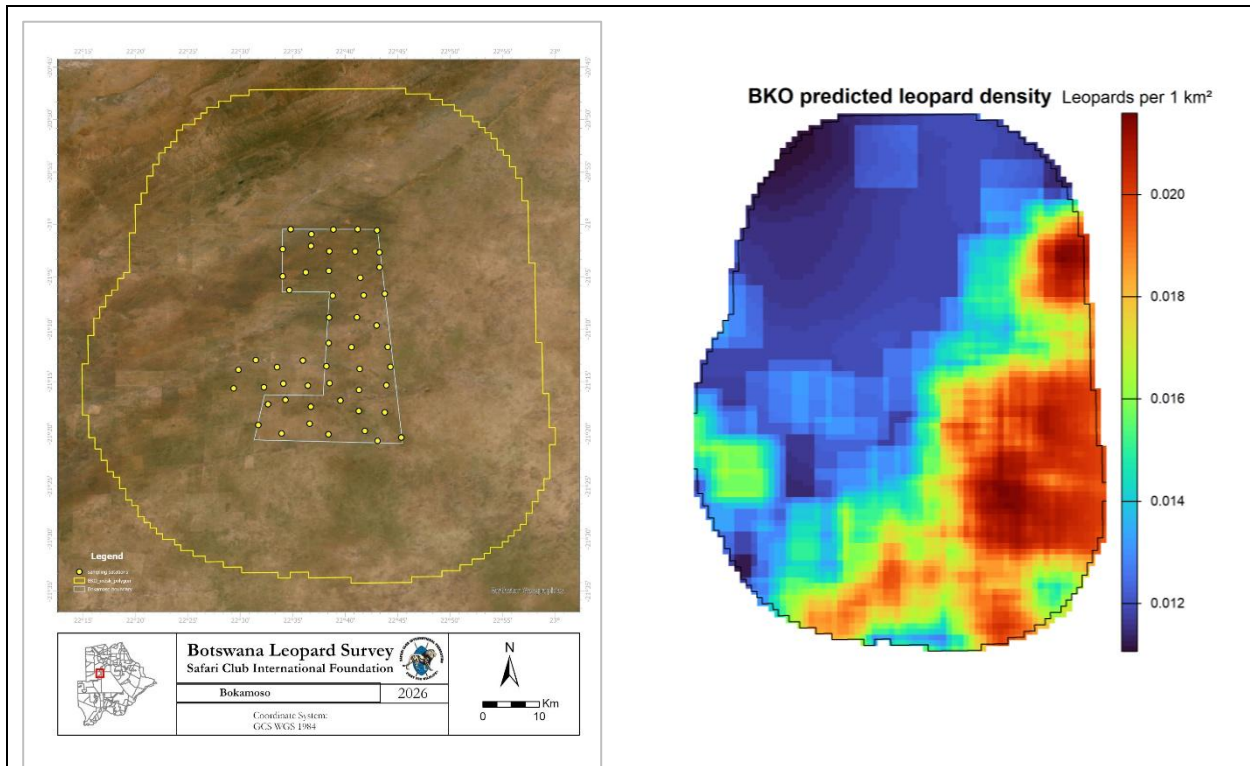
The second page presents a site-specific fact sheet summarizing the principal survey and analytical results. Information includes survey effort, number of camera stations, sampling period, number of independent leopard detections, number and sex of individually identified leopards, and the estimated leopard density. Measures of uncertainty associated with the density estimate, including the standard error, 95% confidence interval, and coefficient of variation, are also provided where applicable. Together, these metrics allow both the magnitude and precision of the site-specific density estimate to be evaluated.

The third page presents photographic examples of one or two individually identified male leopards recorded during the survey. These photographs illustrate the image quality obtained from the camera-trap surveys and the distinctive coat patterns and other characteristics used to identify individual leopards. Where possible, images from opposing cameras are presented to show the characteristic markings on both flanks of an individual.

Collectively, these three-page profiles provide a concise but comprehensive summary of the survey design, sampling results, leopard density estimates, associated uncertainty, and photographic records for each study area. The standardized format is intended to enable DWNP to readily extract, compare, and distribute site-specific information, while also providing a consistent baseline against which results from future surveys can be evaluated. These profiles therefore complement the broader national analyses presented elsewhere in this report by providing the detailed local-level information required for site-specific conservation, management, and long-term monitoring.

BOKAMOSO – WILDLIFE FARM





Bokamoso

LEOPARD DENSITY ESTIMATES

Total

D = 1.74 leopards/100 km²

Females

D = 1.25 leopards/100 km² 95% CI **[0.85; 1.83]**

SE **0.25**

CV **0.20**

Males

D = 0.49 leopards/100 km² 95% CI **[0.33; 0.72]**

SE **0.10**

CV **0.20**

SAMPLING

Number of stations

52

Sampling period

90 days

Average distance between stations

3.35 km

Number of leopard detections

119

Number of leopards identified (males, females, unknown)

29 (M: 12, F:16, U:1)

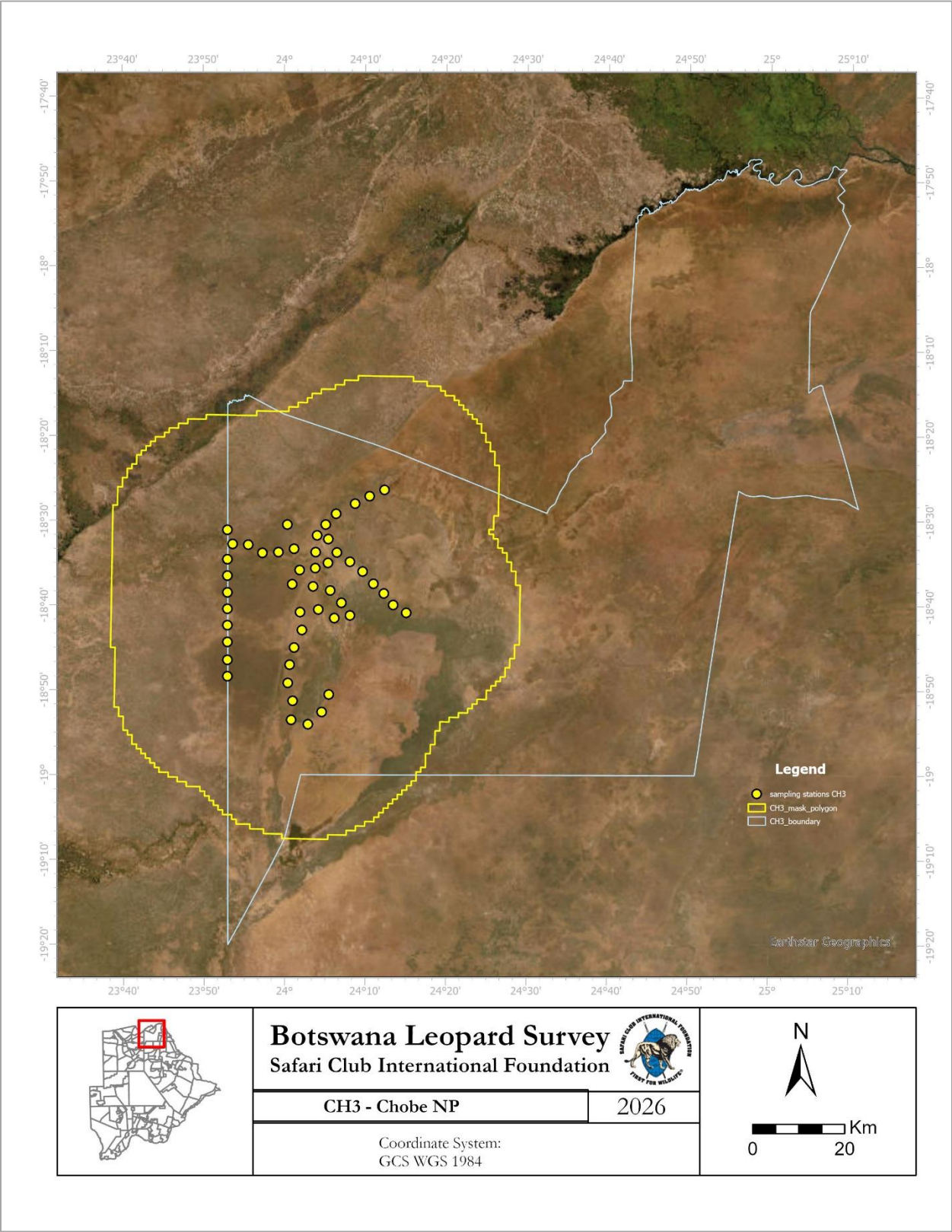
Male BKO_M01

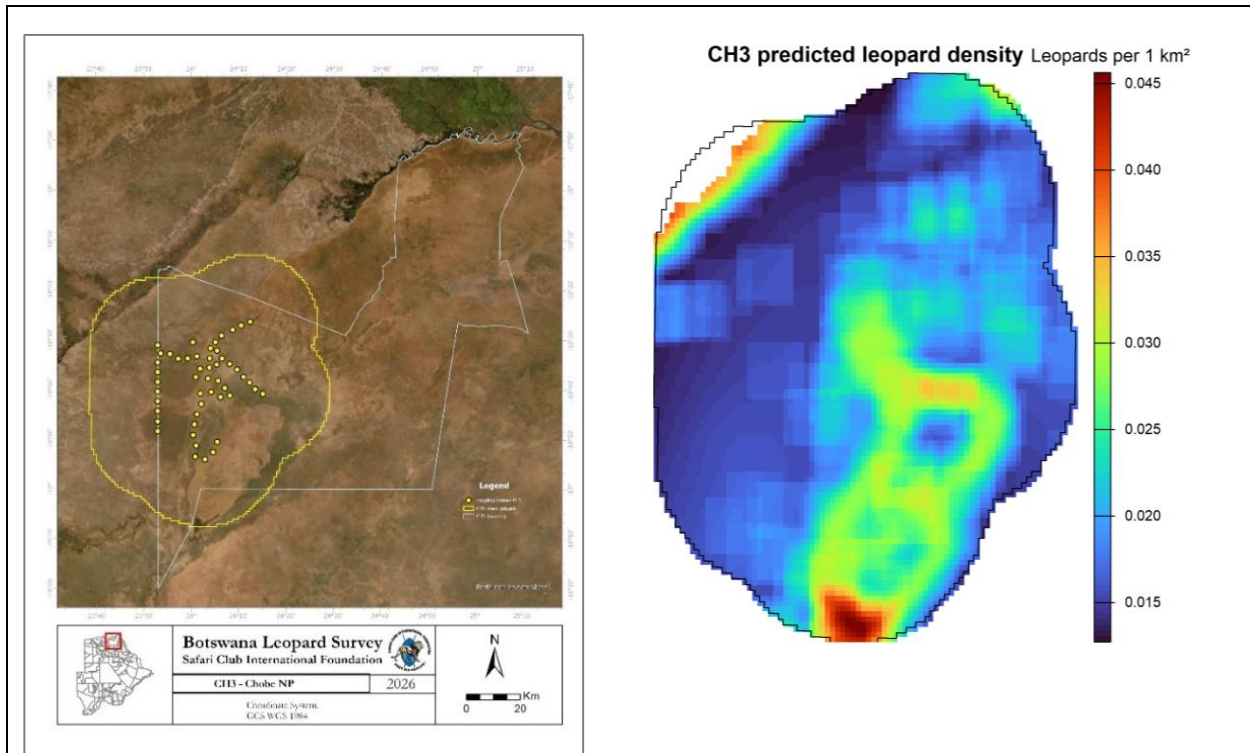


Male BKO_M03



CH3 – CONSERVATION AREA - CHOBE NP





CH3 – Chobe NP

LEOPARD DENSITY ESTIMATES

Total

D = 1.21 leopards/100 km²

Females

D = 0.87 leopards/100 km² 95% CI **[0.57; 1.35]**

SE **0.19**

CV **0.22**

Males

D = 0.34 leopards/100 km² 95% CI **[0.22;0.53]**

SE **0.08**

CV **0.23**

SAMPLING

Number of stations	50
Sampling period	70 days
Average distance between stations	3.5 km
Number of leopard detections	52
Number of leopards identified (males, females, unknown)	22 (M: 8, F:14)

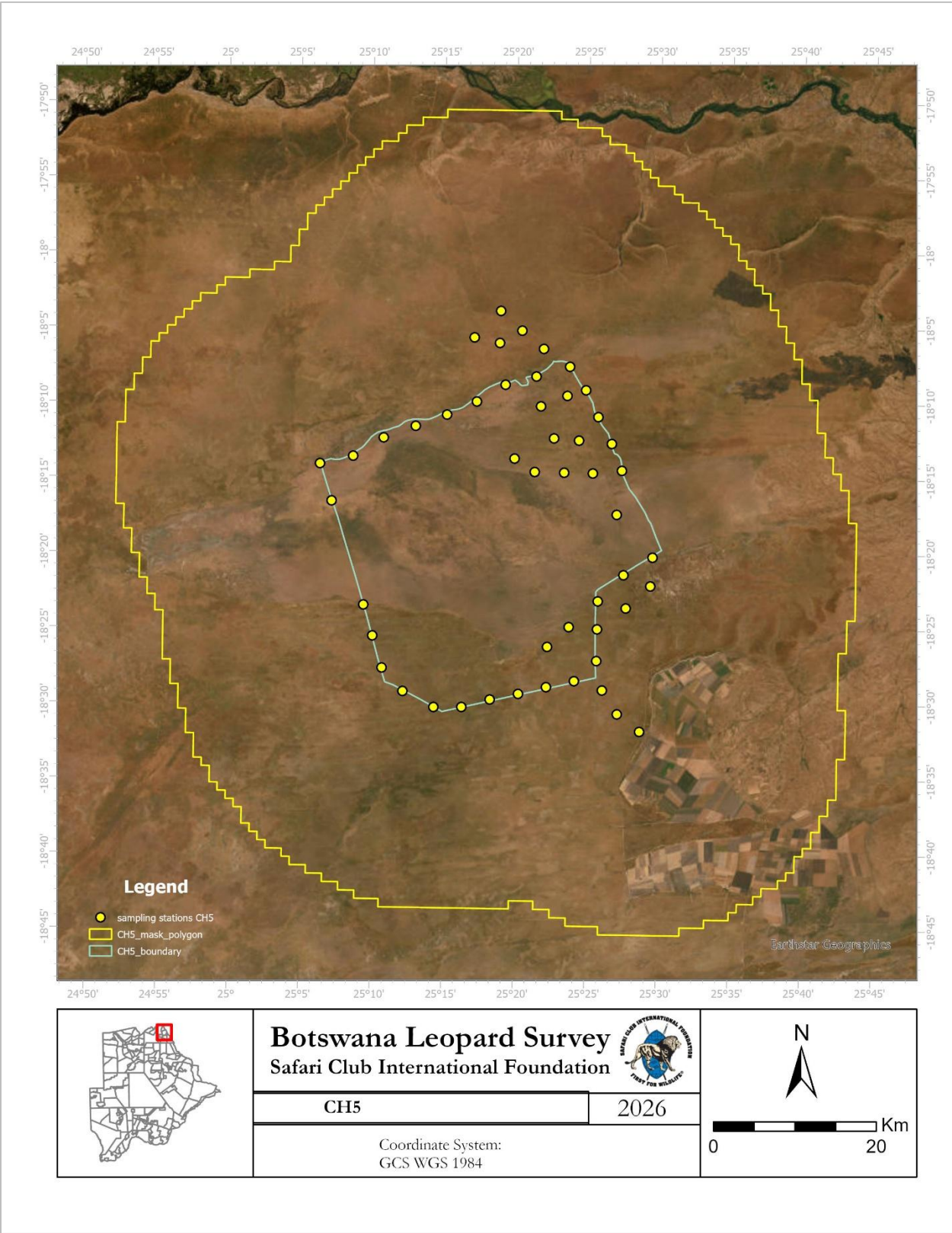
Male CH3_M01

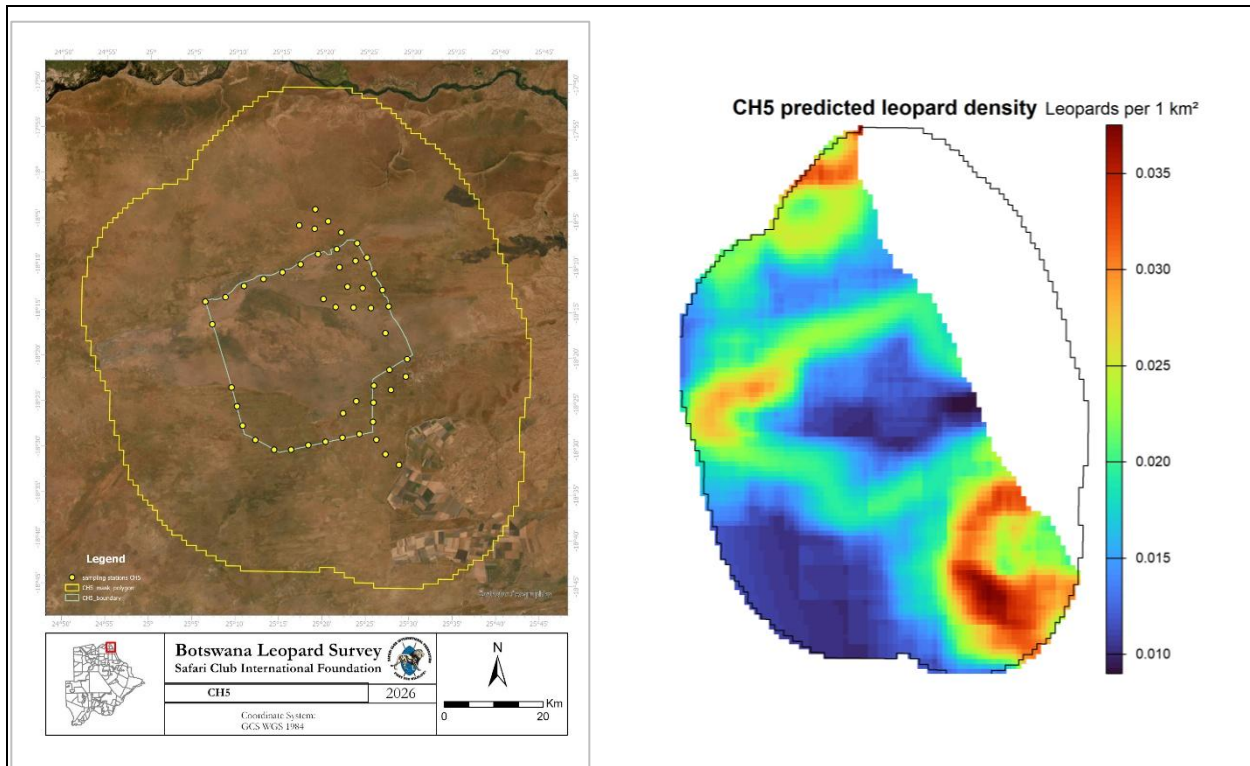


Male CH3_M02



CH5 - COMMUNAL AREA



**CH5****LEOPARD DENSITY ESTIMATES****Total****D = 1.43 leopards/100 km²****Females****D = 1.03 leopards/100 km² 95% CI [0.72; 1.47]****SE 0.19****CV 0.18****Males****D = 0.40 leopards/100 km² 95% CI [0.28; 0.58]****SE 0.08****CV 0.19****SAMPLING****Number of stations****50****Sampling period****140 days****Average distance between stations****3.52 km****Number of leopard detections****87****Number of leopards identified (males, females, unknown)****33 (M: 14, F:19)**

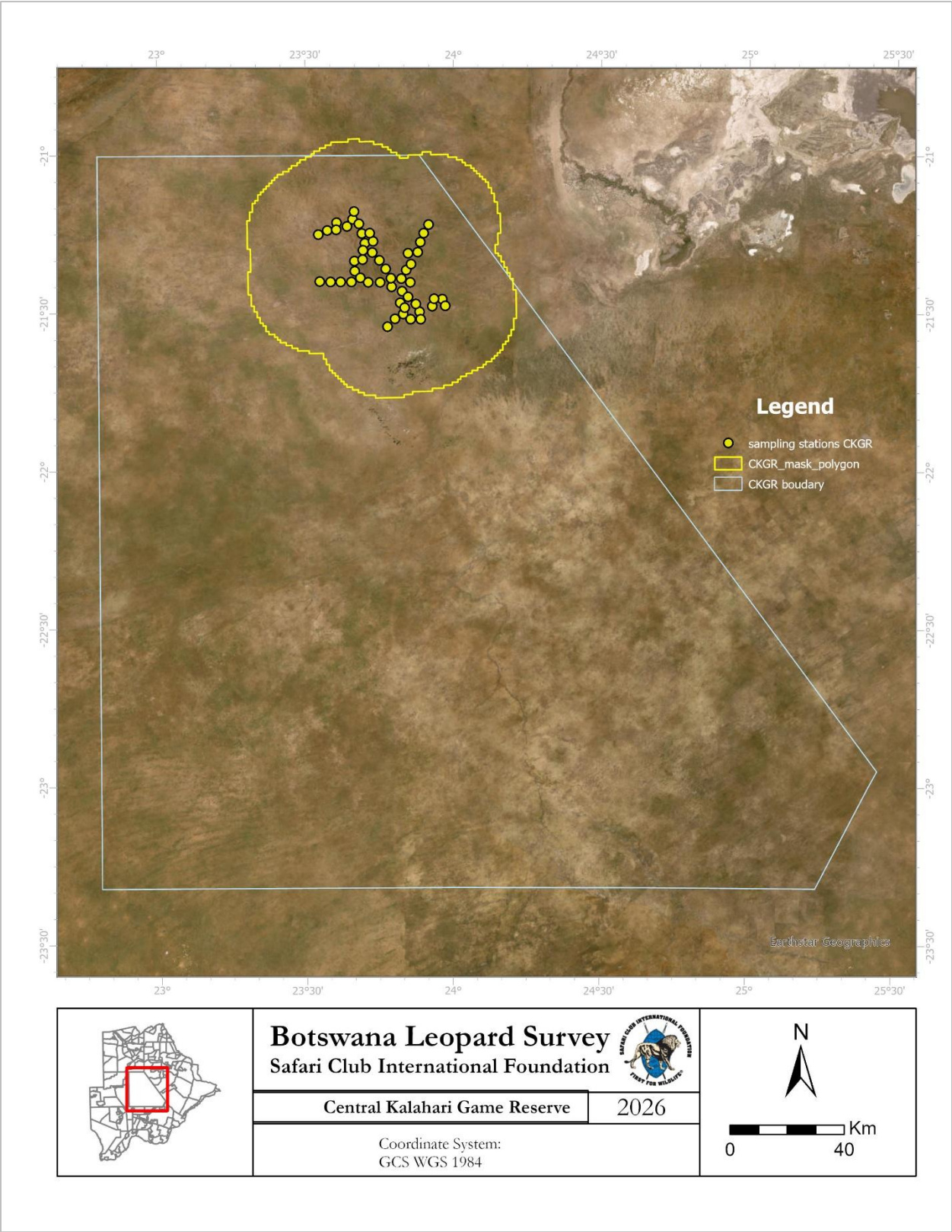
Male CH5_M03

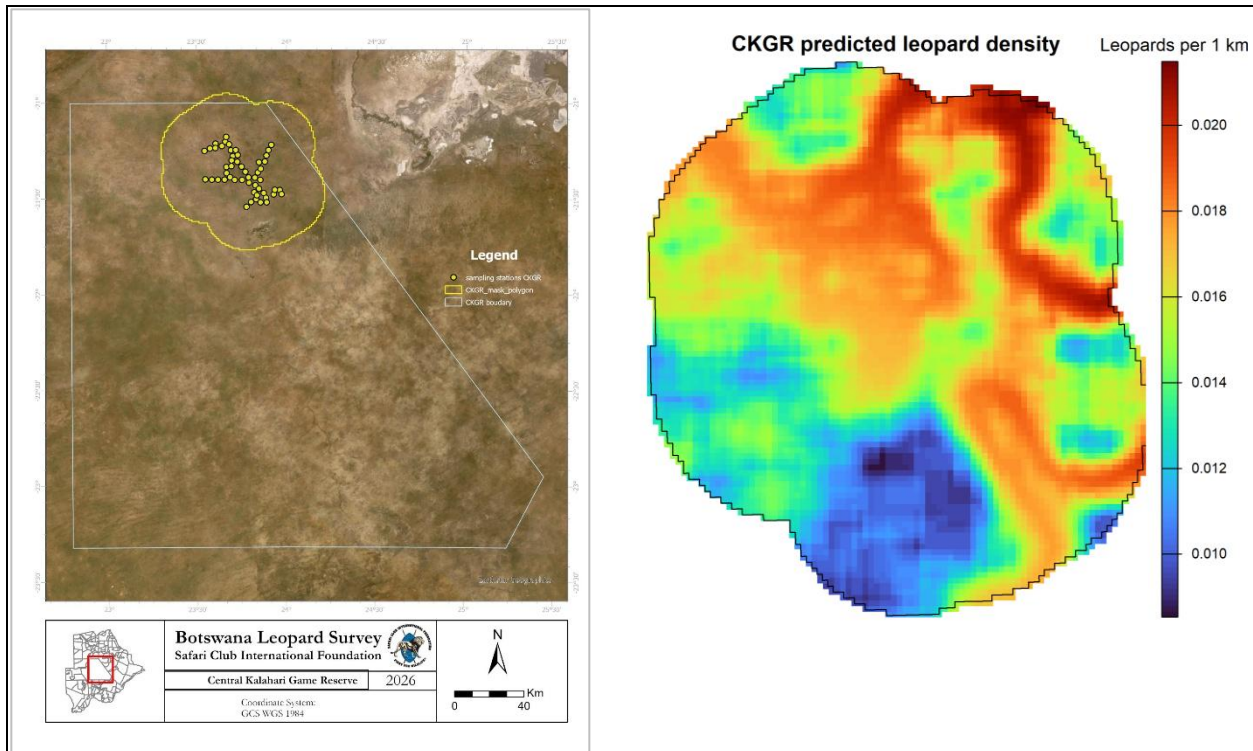


Male CH5_M04



CKGR – CONSERVATION AREA - CENTRAL KALAHARI GAME RESERVE



**CKGR – Central Kalahari Game Reserve****LEOPARD DENSITY ESTIMATES****Total****D = 2.67 leopards/100 km²****Females****D = 1.92 leopards/100 km² 95% CI [1.42; 2.59]****SE 0.29****CV 0.15****Males****D = 0.75 leopards/100 km² 95% CI [0.55; 1.02]****SE 0.12****CV 0.16****SAMPLING****Number of stations****52****Sampling period****89 days****Average distance between stations****3.37 km****Number of leopard detections****211****Number of leopards identified (males, females, unknown)****56 (M: 27, F:22, U:7)**

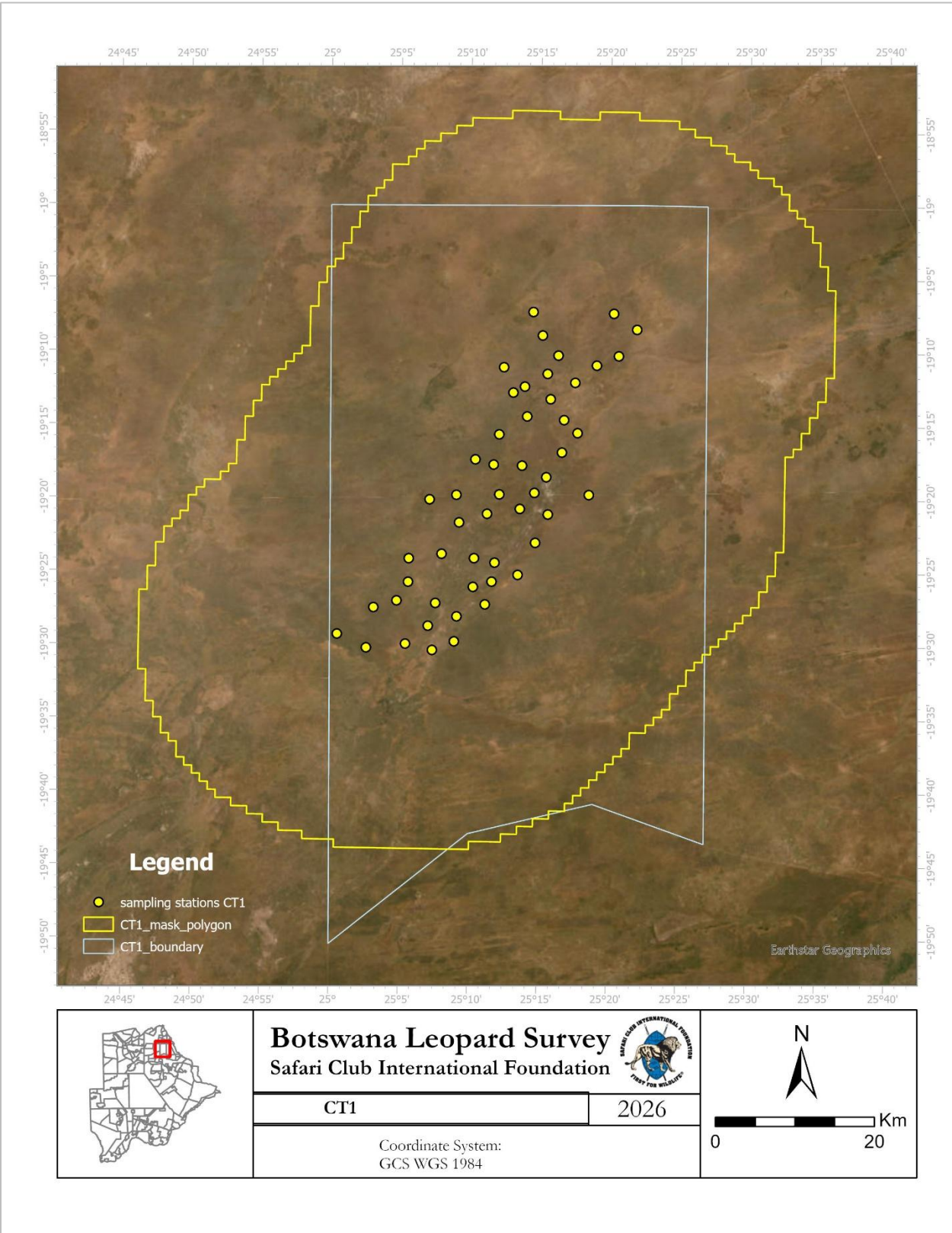
Male CKGR_M02

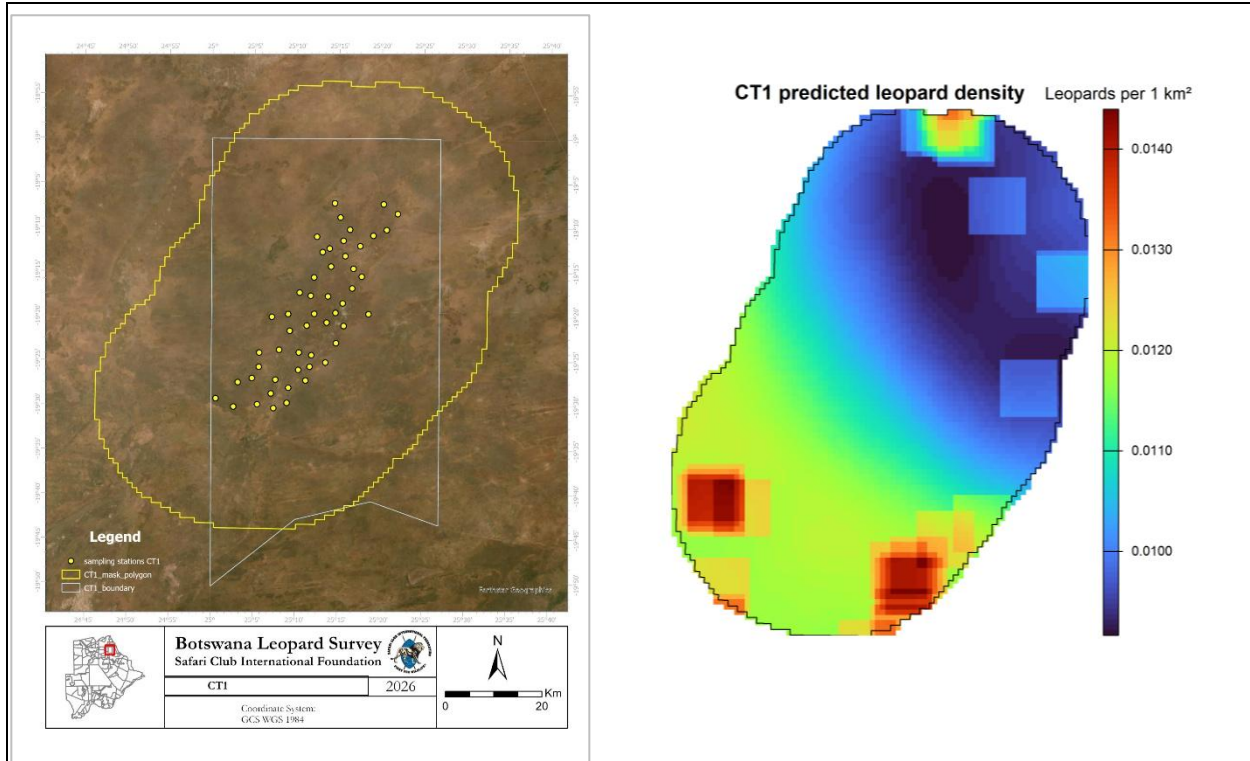


Male CKGR_M06



CT1 – HUNTING CONCESSION



**CT1****LEOPARD DENSITY ESTIMATES****Total****D = 1.67 leopards/100 km²****Females****D = 1.20 leopards/100 km² 95% CI [0.80; 1.82]****SE 0.26****CV 0.21****Males****D = 0.47 leopards/100 km² 95% CI [0.31; 0.72]****SE 0.10****CV 0.22****SAMPLING****Number of stations****52****Sampling period****65 days****Average distance between stations****3.01 km****Number of leopard detections****76****Number of leopards identified (males, females, unknown)****24 (M: 9, F:15)**

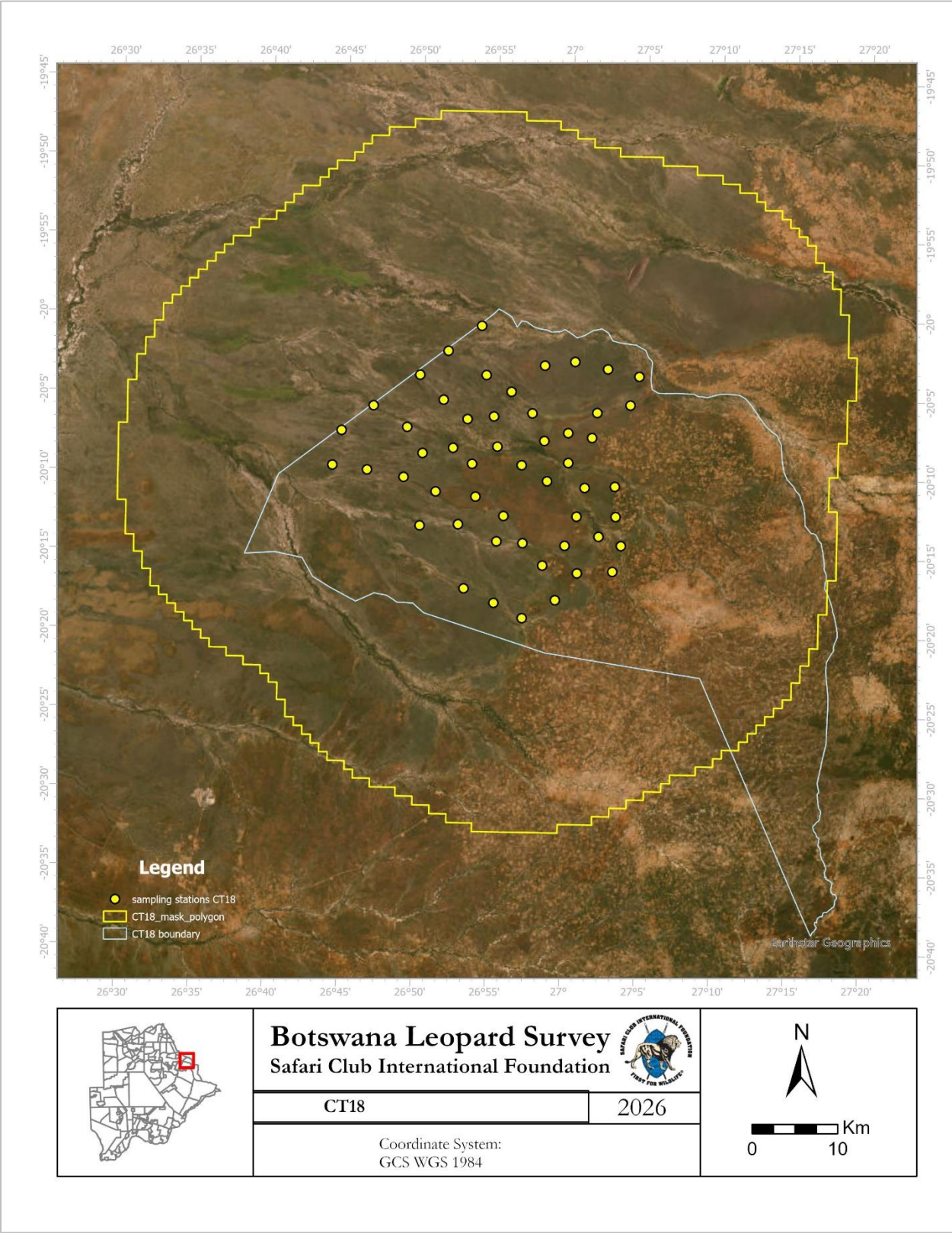
Male CT1_M01

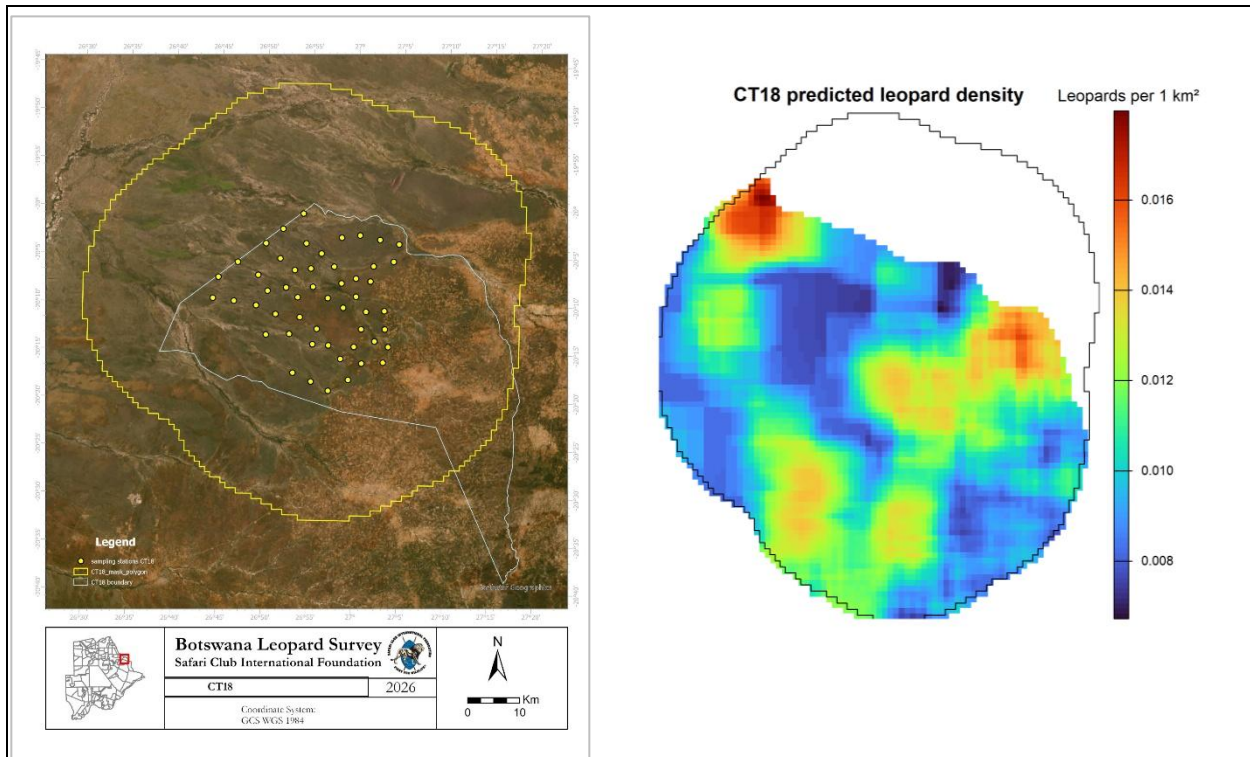


Male CT1_M02



CT18 – COMMUNAL AREA



**CT18****LEOPARD DENSITY ESTIMATES****Total****D = 0.28 leopards/100 km²****Females****D = 0.20 leopards/100 km² 95% CI [0.08; 0.49]****SE 0.10****CV 0.47****Males****D = 0.08 leopards/100 km² 95% CI [0.03; 0.19]****SE 0.04****CV 0.48****SAMPLING****Number of stations****52****Sampling period****150 days****Average distance between stations****3.50 km****Number of leopard detections****27****Number of leopards identified (males, females, unknown)****5 (M: 2, F:3)**

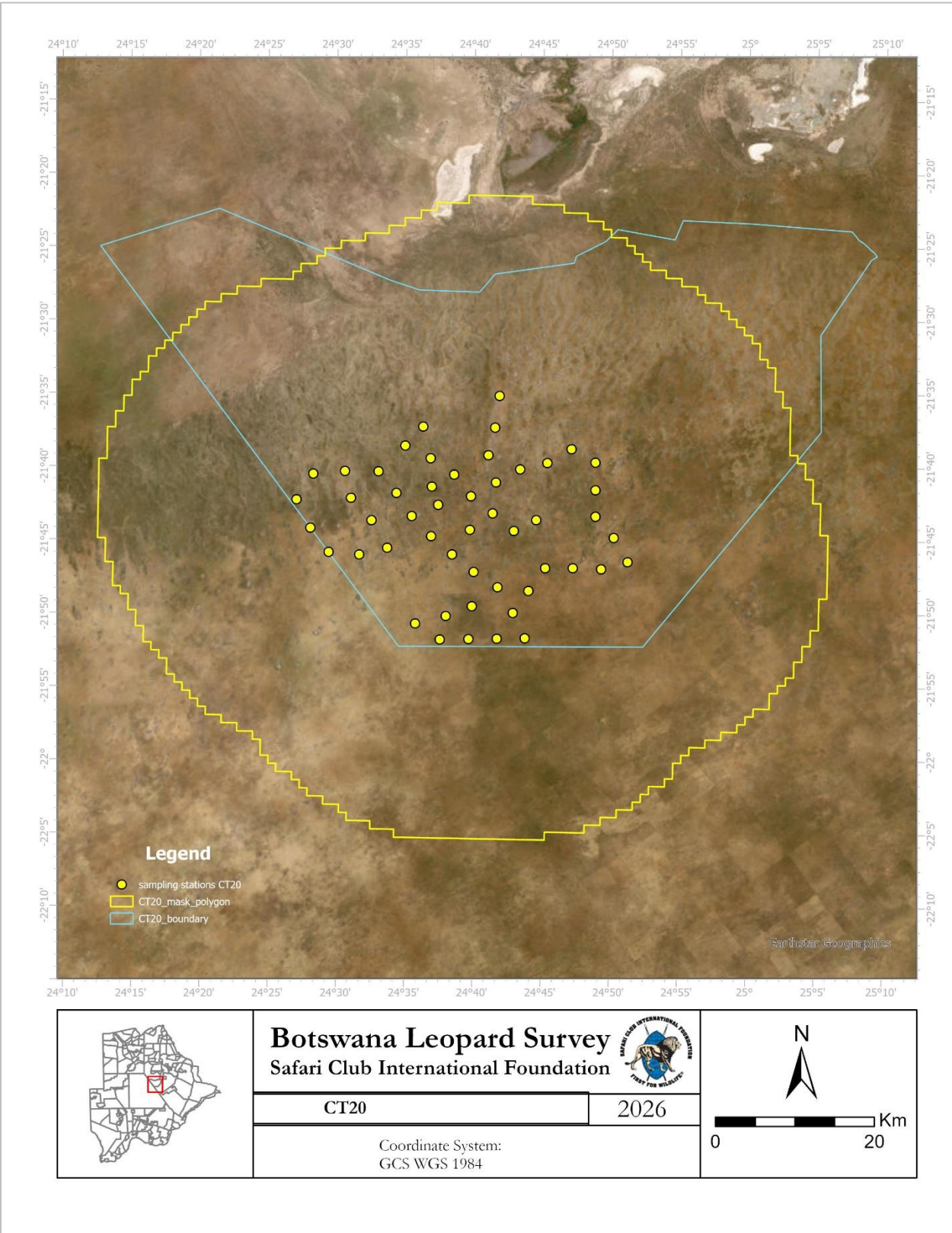
Male CT18_M01

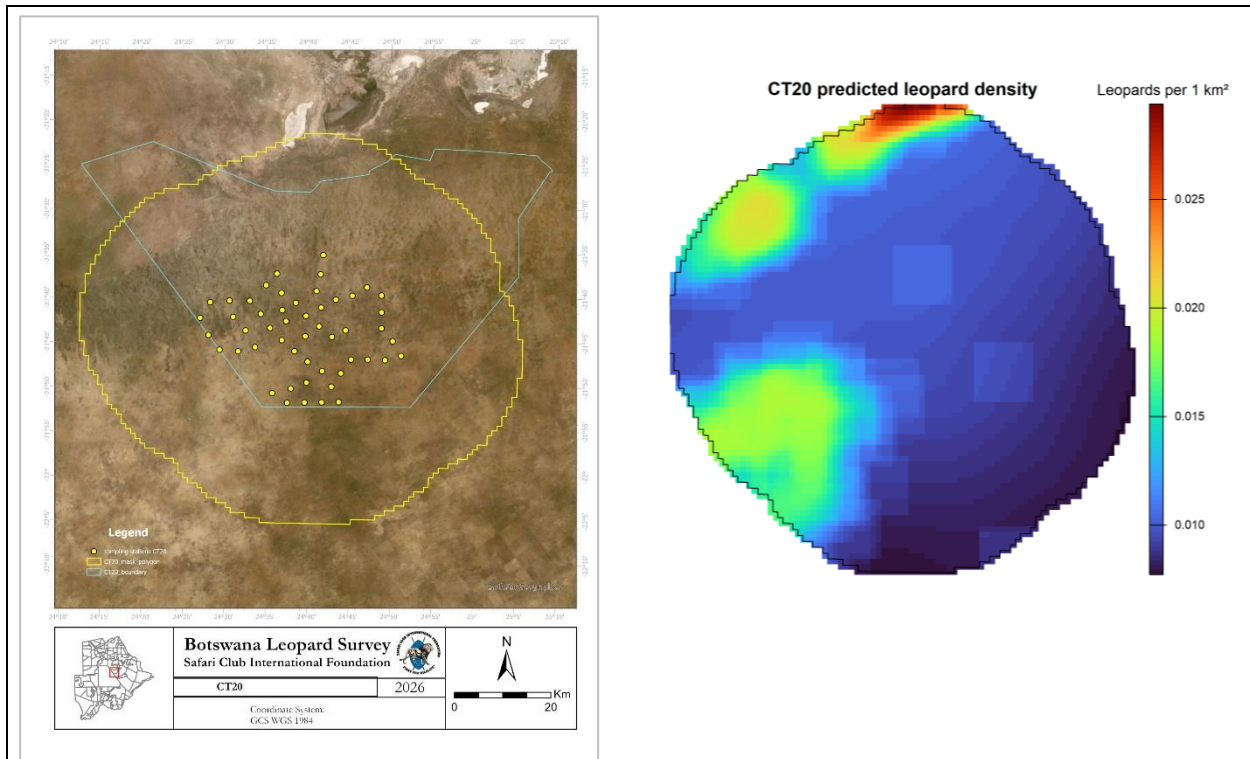


Male CT18_M02



CT20 – WILDLIFE FARM



**CT20****LEOPARD DENSITY ESTIMATES****Total****D = 0.93 leopards/100 km²****Females****D = 0.67 leopards/100 km² 95% CI [0.39; 1.14]****SE 0.19****CV 0.28****Males****D = 0.26 leopards/100 km² 95% CI [0.15; 0.45]****SE 0.07****CV 0.28****SAMPLING****Number of stations****51****Sampling period****70 days****Average distance between stations****3.50 km****Number of leopard detections****41****Number of leopards identified (males, females, unknown)****16 (M: 4, F:10, U:2)**

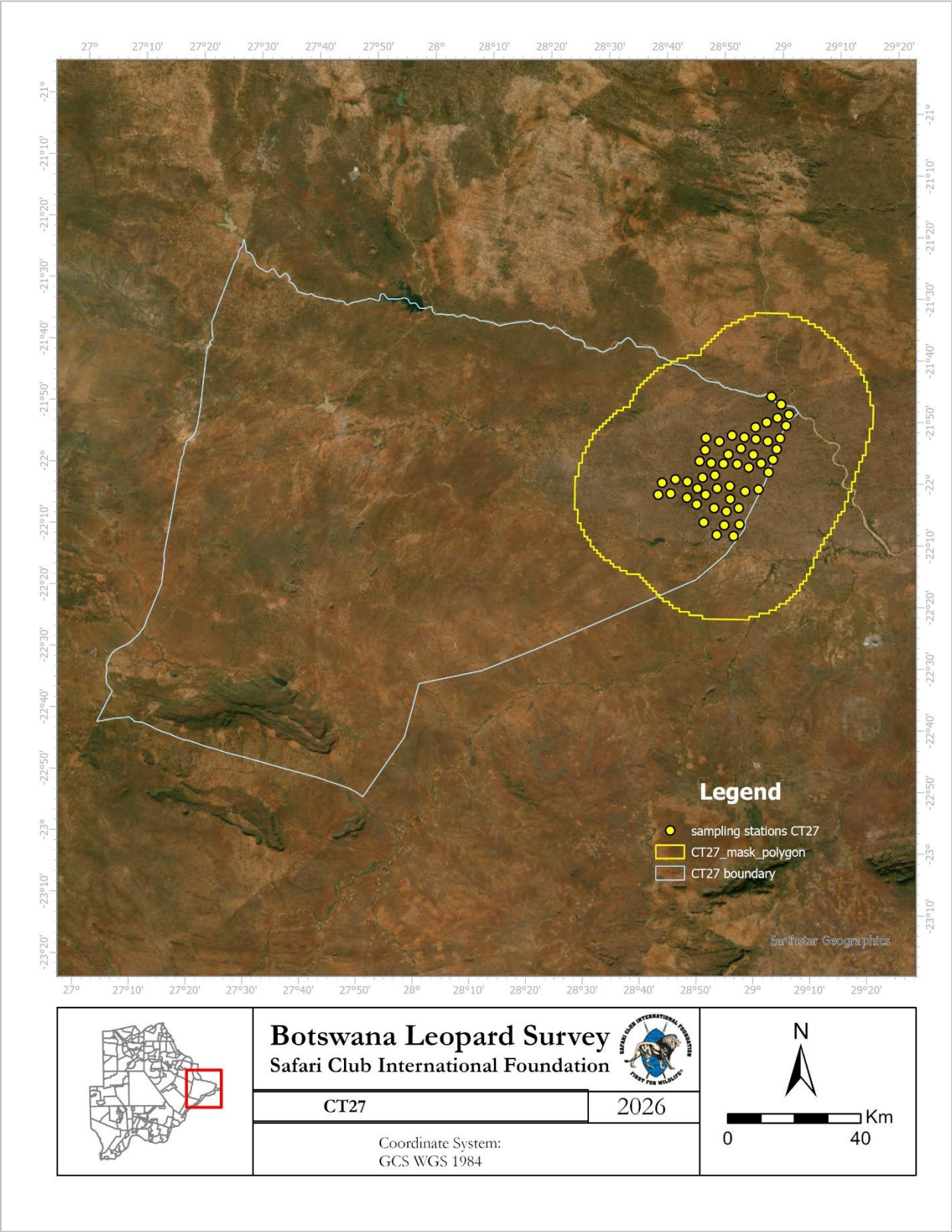
Male CT20_M01

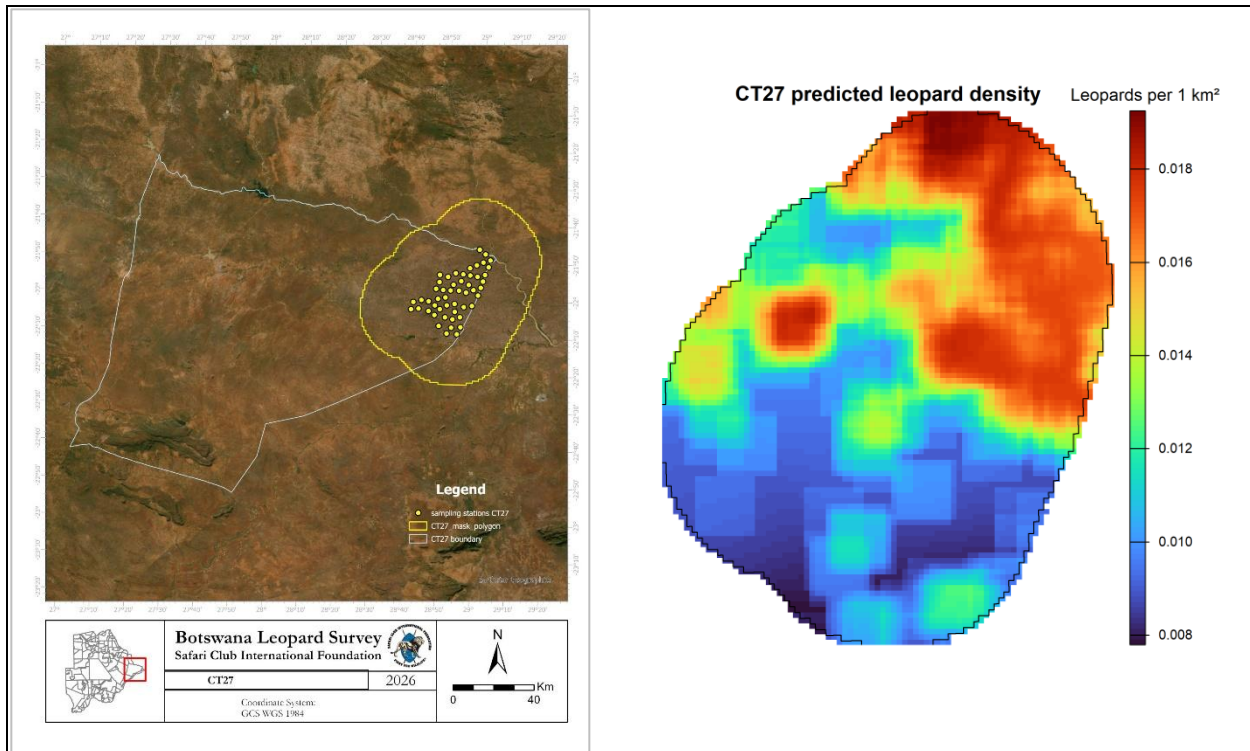


Male CT20_M03



CT27 – COMMUNAL AREA



**CT27****LEOPARD DENSITY ESTIMATES****Total****D = 0.15 leopards/100 km²****Females****D = 0.11 leopards/100 km² 95% CI [0.04; 0.36]****SE 0.07****CV 0.63****Males****D = 0.04 leopards/100 km² 95% CI [0.01; 0.14]****SE 0.03****CV 0.63****SAMPLING****Number of stations****51****Sampling period****160 days****Average distance between stations****3.58 km****Number of leopard detections****14****Number of leopards identified (males, females, unknown)****5 (M: 2, F:1, U:2)**

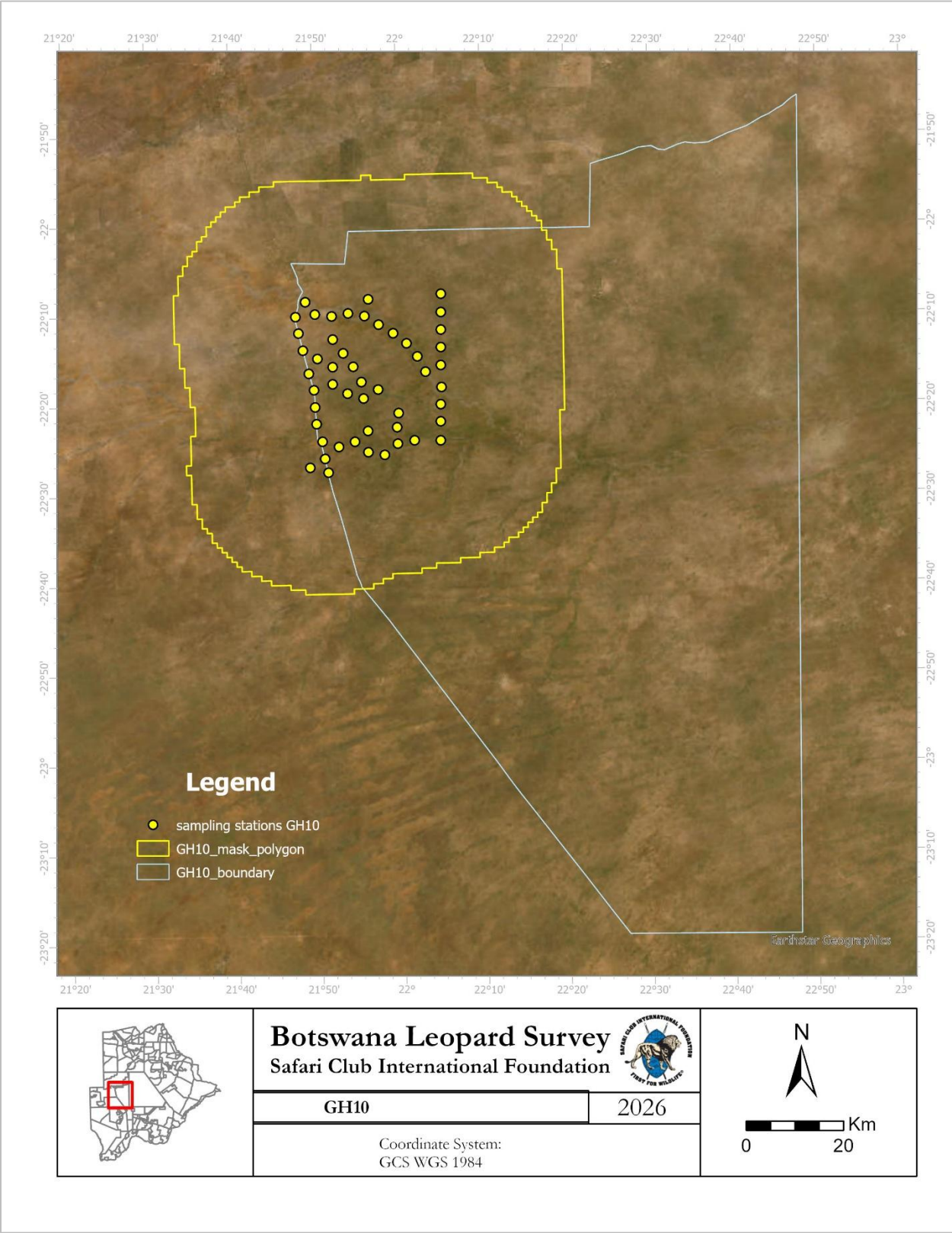
Male CT27_M01

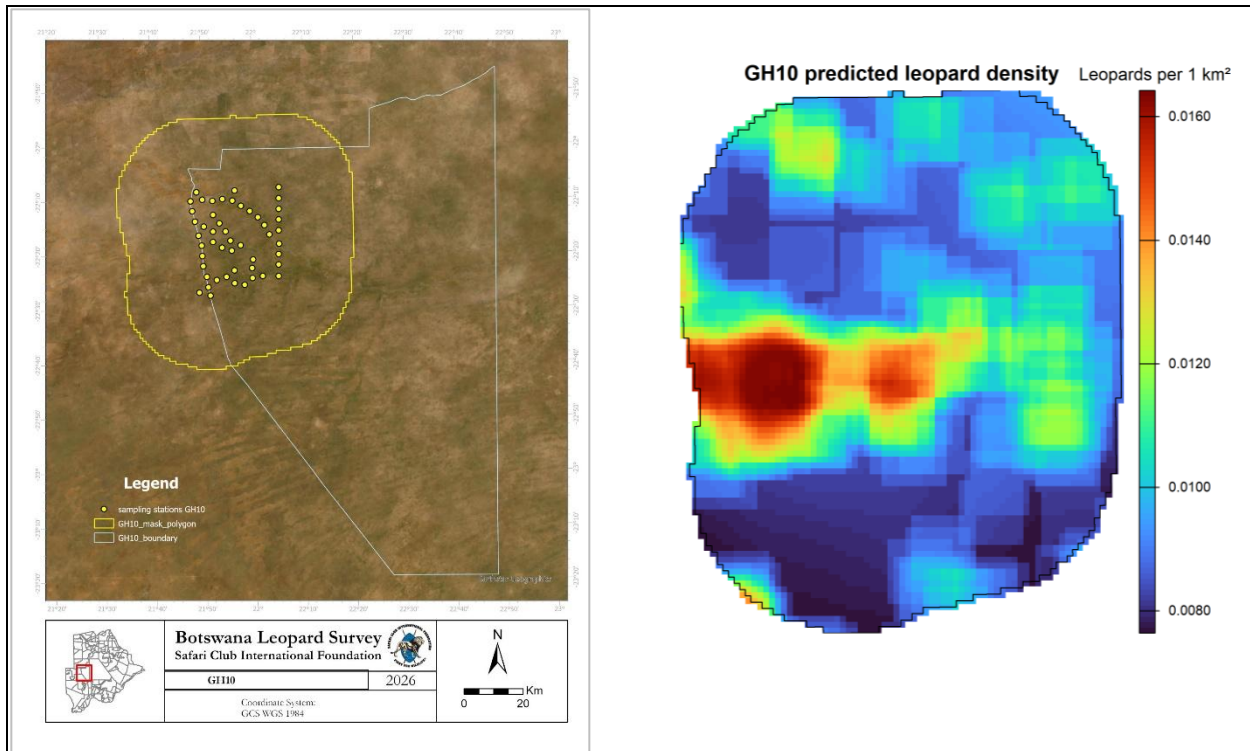


Male CT27_M02



GH10 – COMMUNAL AREA



**GH10****LEOPARD DENSITY ESTIMATES****Total****D = 0.57 leopards/100 km²****Females****D = 0.41 leopards/100 km²** 95% CI [0.21; 0.80]

SE 0.14

CV 0.35

Males**D = 0.16 leopards/100 km²** 95% CI [0.08; 0.31]

SE 0.06

CV 0.35

SAMPLING**Number of stations****50****Sampling period****65 days****Average distance between stations****3.45 km****Number of leopard detections****35****Number of leopards identified (males, females, unknown)****9 (M: 4, F:5)**

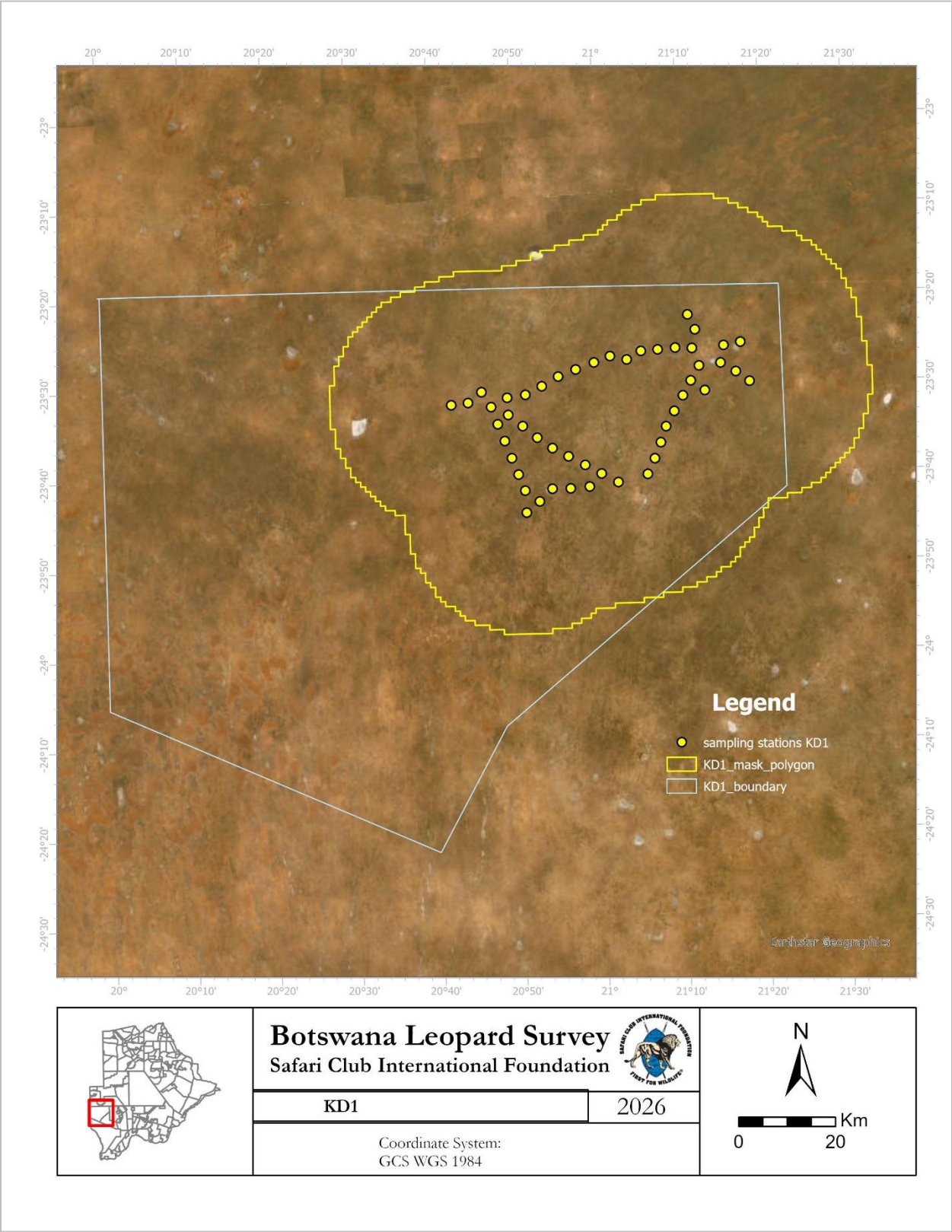
Male GH10_M01

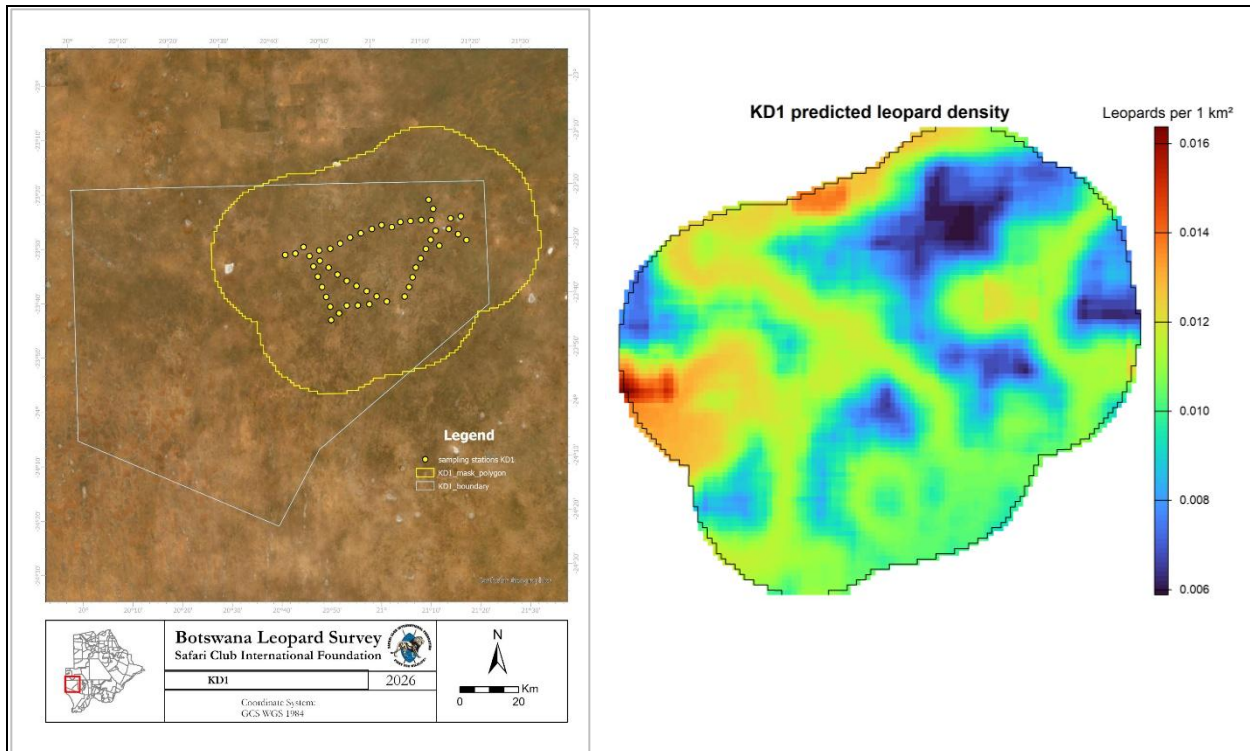


Male GH10_M02



KD1 – COMMUNAL AREA



**KD1****LEOPARD DENSITY ESTIMATES****Total****D = 0.92 leopards/100 km²****Females****D = 0.66 leopards/100 km²**

95%
CI [0.40; 1.09]
SE 0.17
CV 0.26

Males**D = 0.26 leopards/100 km²**

95%
CI [0.15; 0.43]
SE 0.07
CV 0.26

SAMPLING**Number of stations****50****Sampling period****60 days****Average distance between stations****3.54 km****Number of leopard detections****37****Number of leopards identified (males, females, unknown)****19 (M: 5, F:11, U:3)**

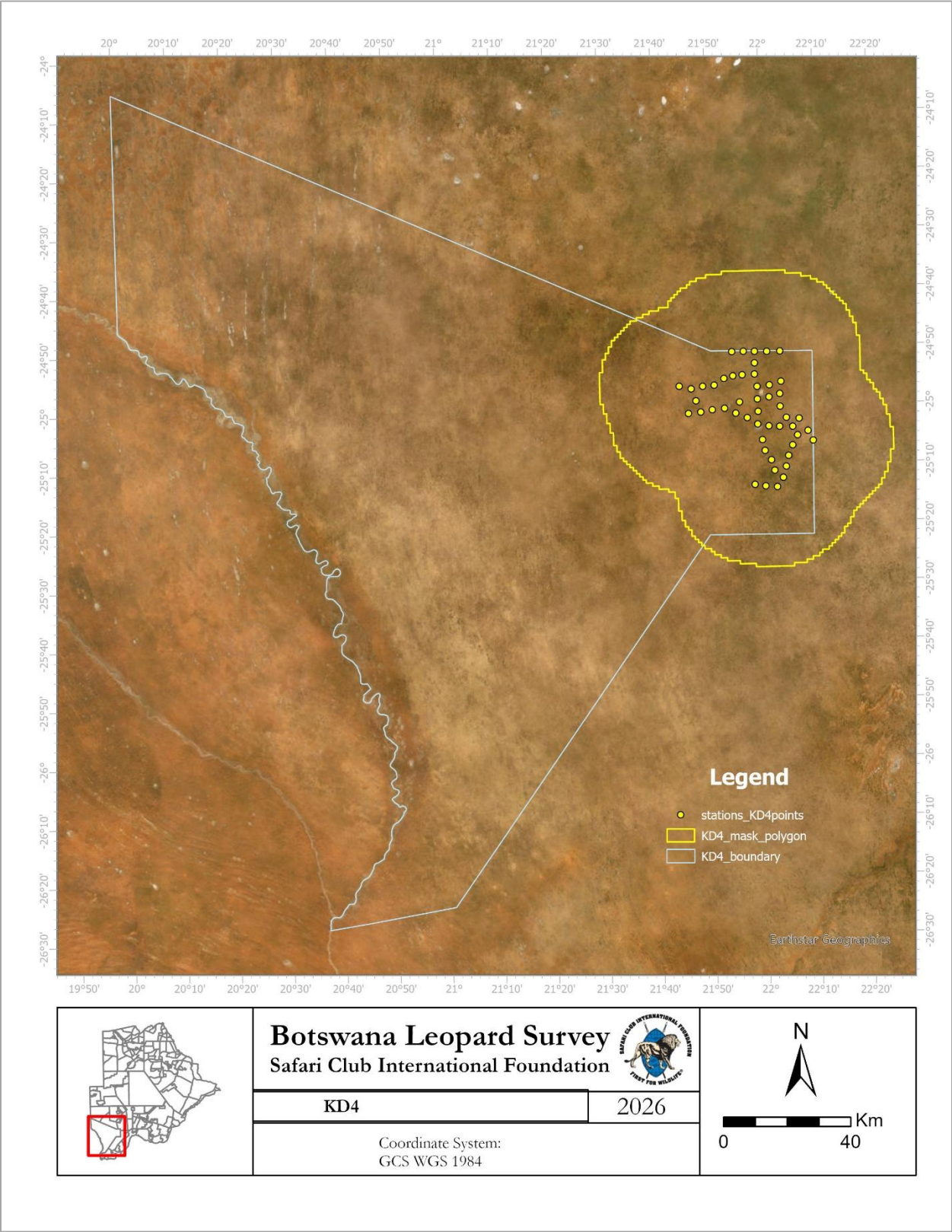
Male KD1_M02

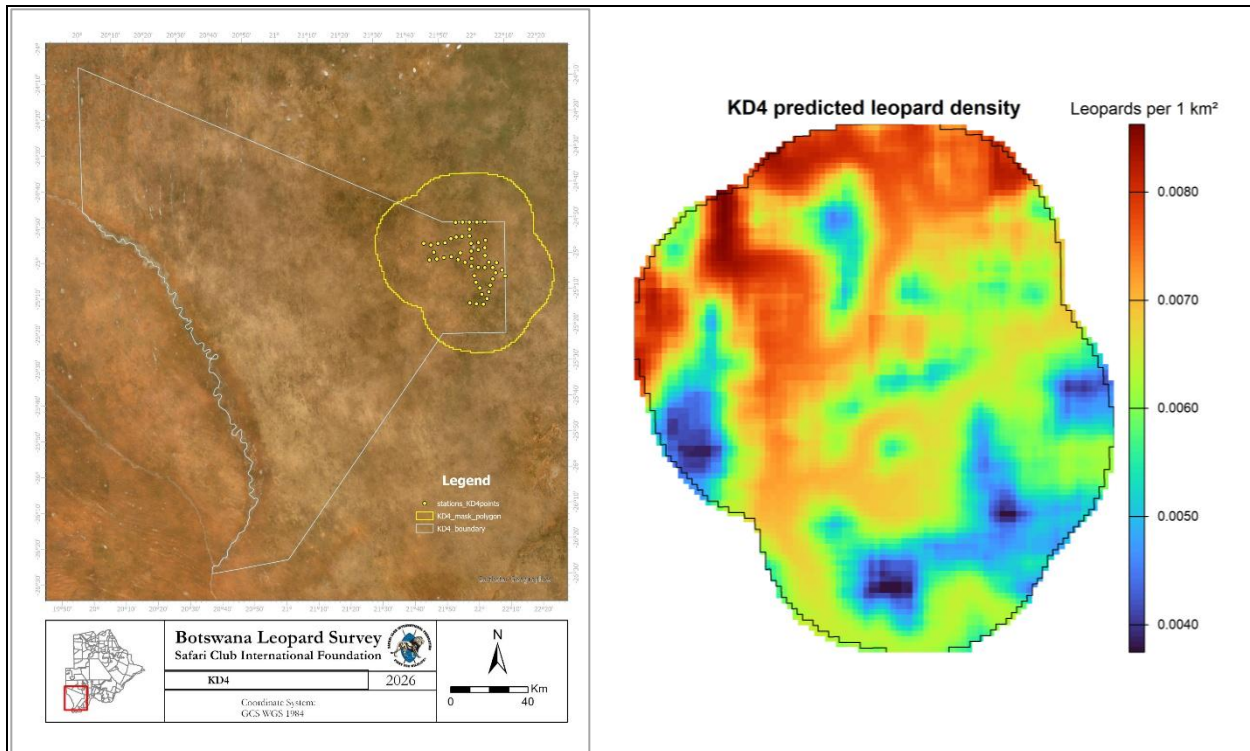


Male KD1_M03



KD4 – CONSERVATION AREA (KGALAGADI TRANSFRONTIER PARK)





KD4 - Kgalagadi Transfrontier Park

LEOPARD DENSITY ESTIMATES

Total

D = 1.61 leopards/100 km²

Females

D = 1.16 leopards/100 km² 95% CI [0.77; 1.74]

SE 0.24

CV 0.21

Males

D = 0.45 leopards/100 km² 95% CI [0.30; 0.69]

SE 0.10

CV 0.21

SAMPLING

Number of stations

50

Sampling period

60 days

Average distance between stations

3.57 km

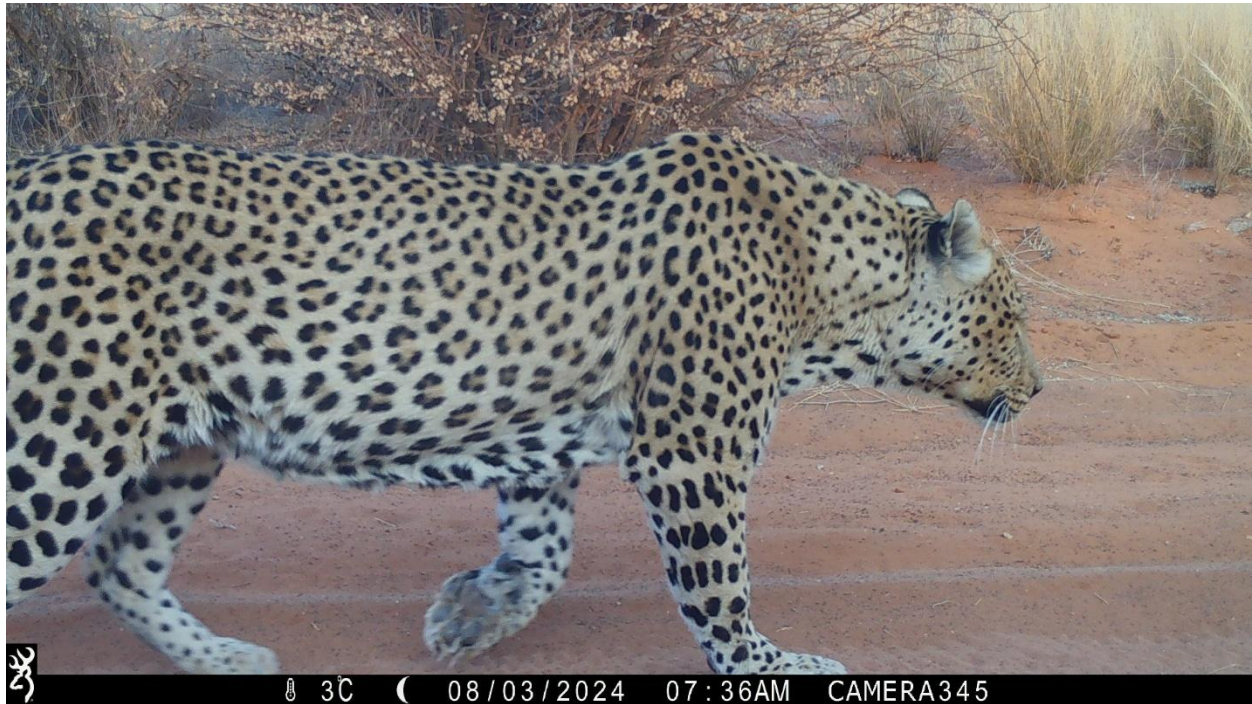
Number of leopard detections

70

Number of leopards identified (males, females, unknown)

25 (M: 11, F:14)

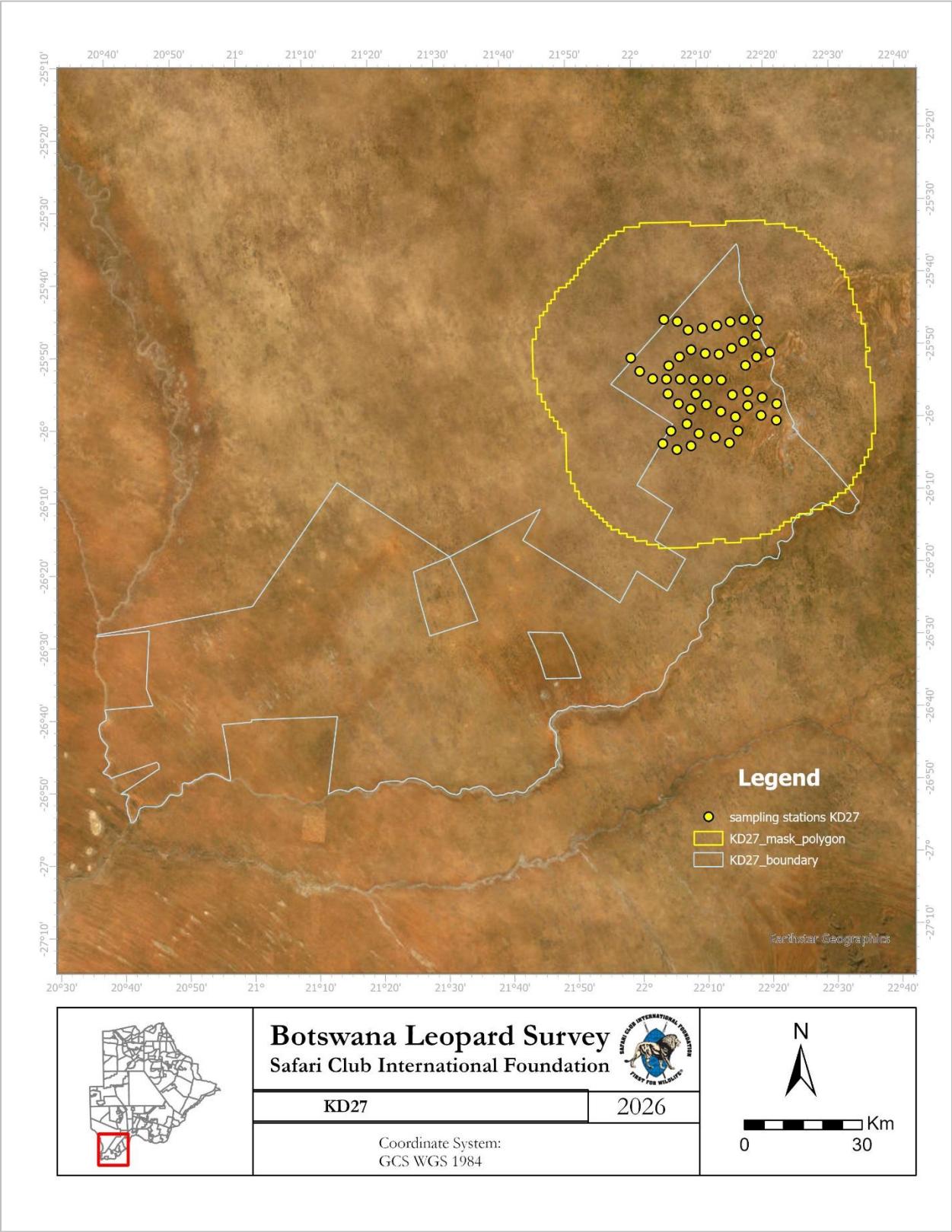
Male KD4_M02

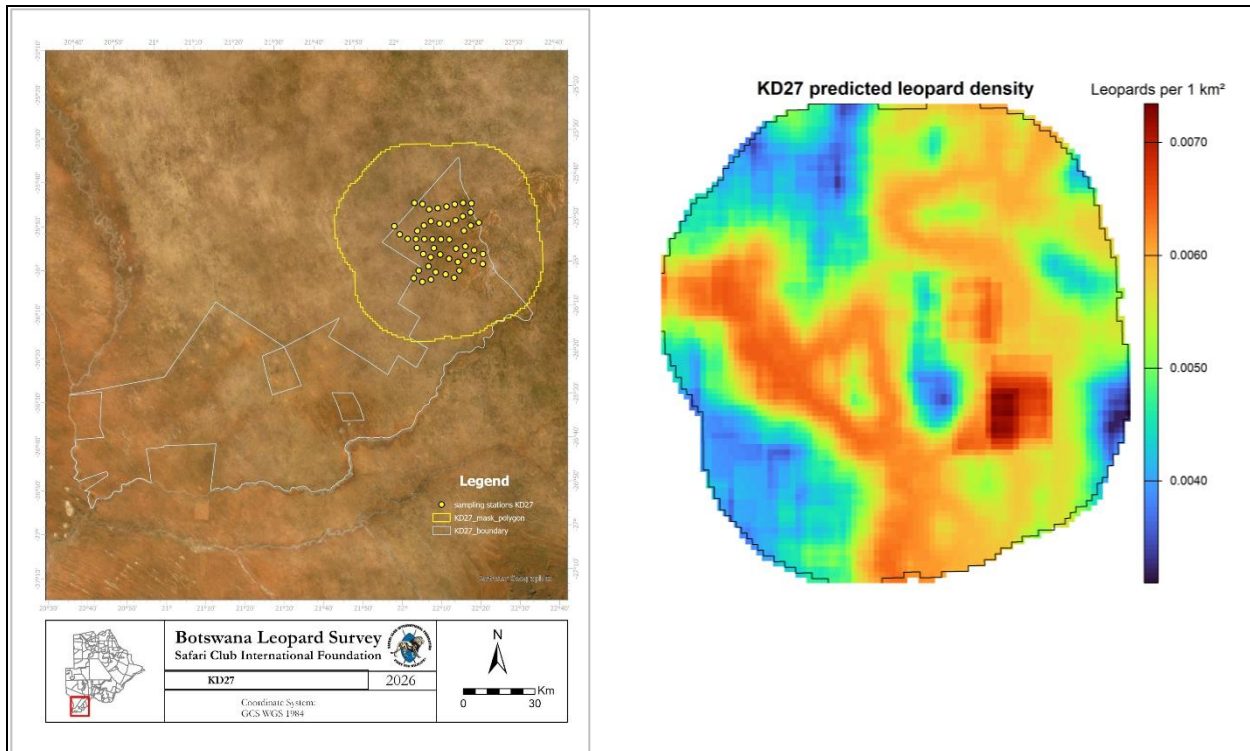


Male KD4_M04



KD27 – COMMUNAL AREA

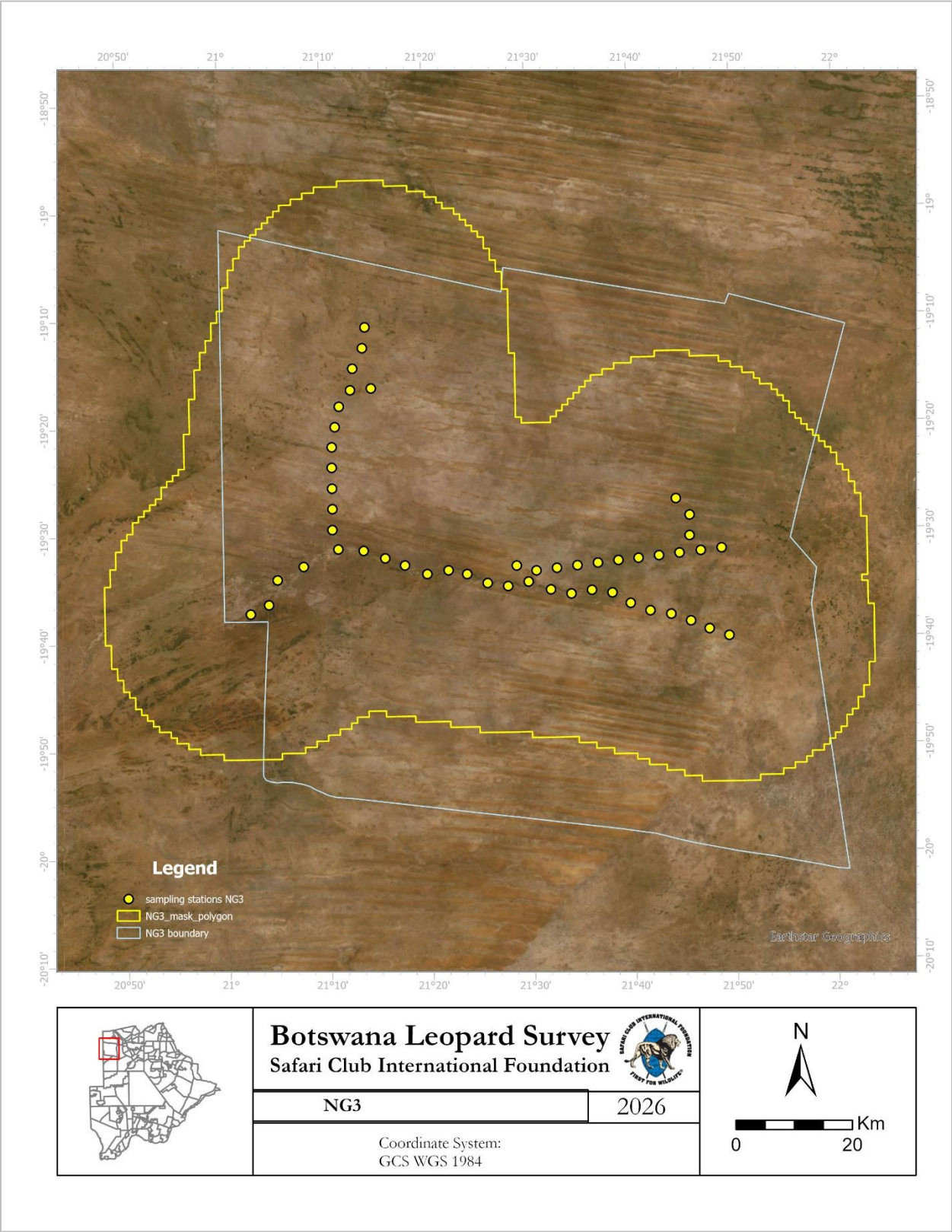


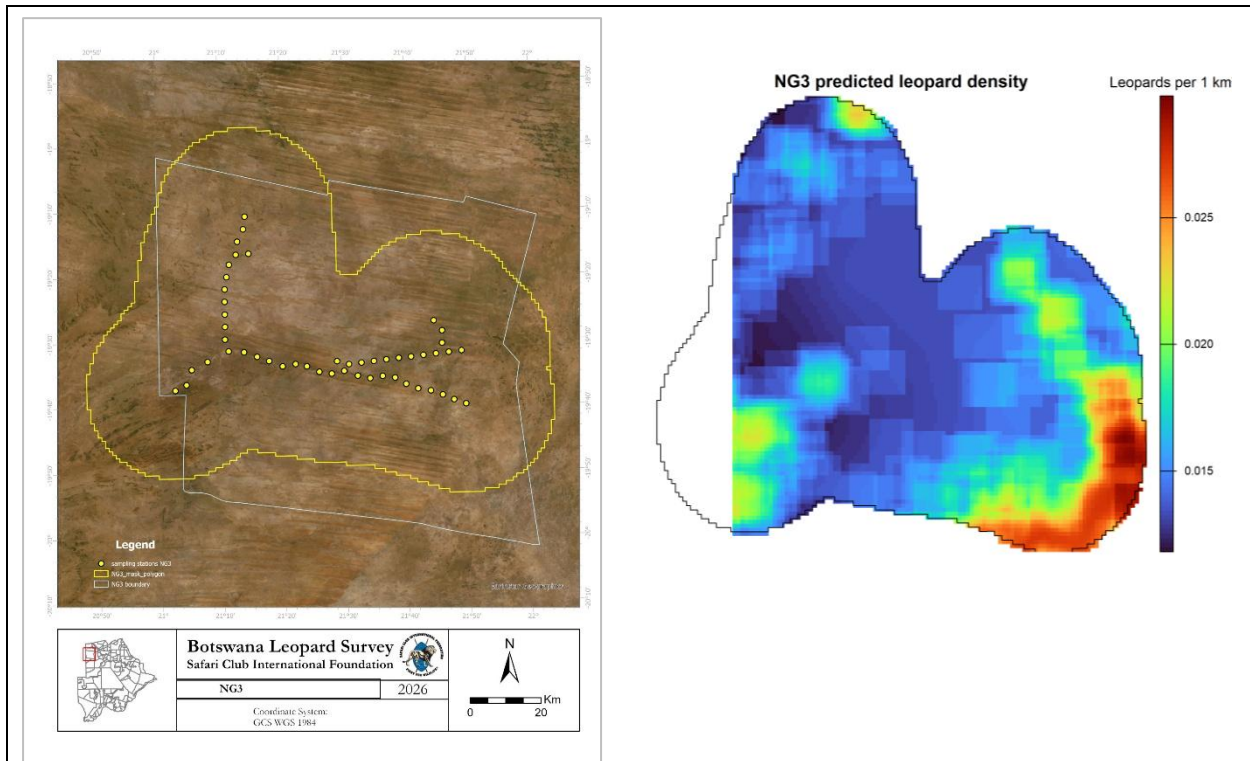
**KD27****LEOPARD DENSITY ESTIMATES****Total****D = 0.26 leopards/100 km²****Females****D = 0.19 leopards/100 km² 95% CI [0.07; 0.51]****SE 0.10****CV 0.54****Males****D = 0.07 leopards/100 km² 95% CI [0.03; 0.20]****SE 0.04****CV 0.54****SAMPLING****Number of stations****50****Sampling period****60 days****Average distance between stations****3.62 km****Number of leopard detections****8****Number of leopards identified (males, females, unknown)****4 (M: 1, F:3)**

Male KD27_M01



NG3 – COMMUNAL AREA



**NG3****LEOPARD DENSITY ESTIMATES****Total****D = 0.52 leopards/100 km²****Females****D = 0.37 leopards/100 km² 95% CI [0.19; 0.72]****SE 0.13****CV 0.35****Males****D = 0.15 leopards/100 km² 95% CI [0.07; 0.28]****SE 0.05****CV 0.35****SAMPLING****Number of stations****50****Sampling period****60 days****Average distance between stations****3.53 km****Number of leopard detections****17****Number of leopards identified (males, females, unknown)****9 (M: 3, F:6)**

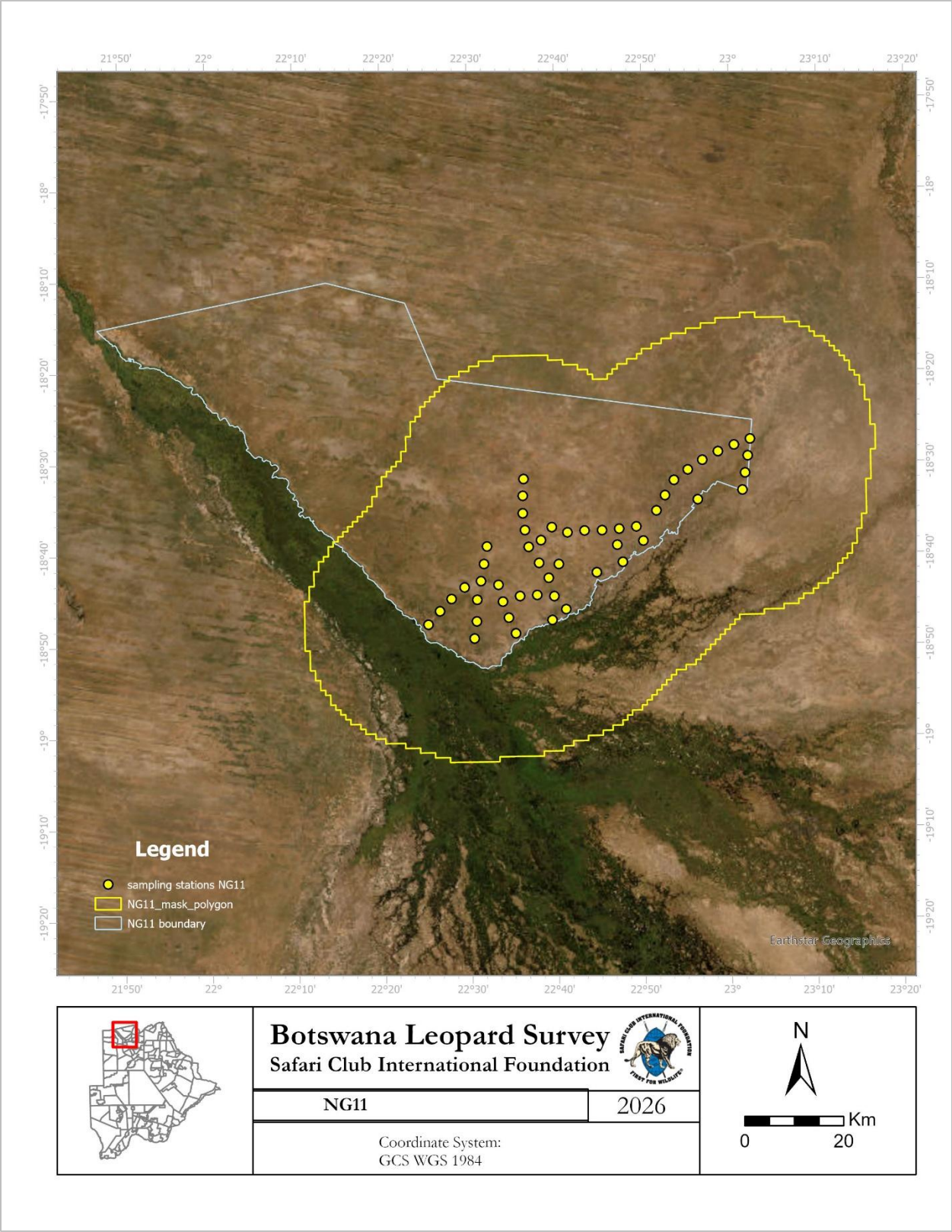
Male NG3_M01

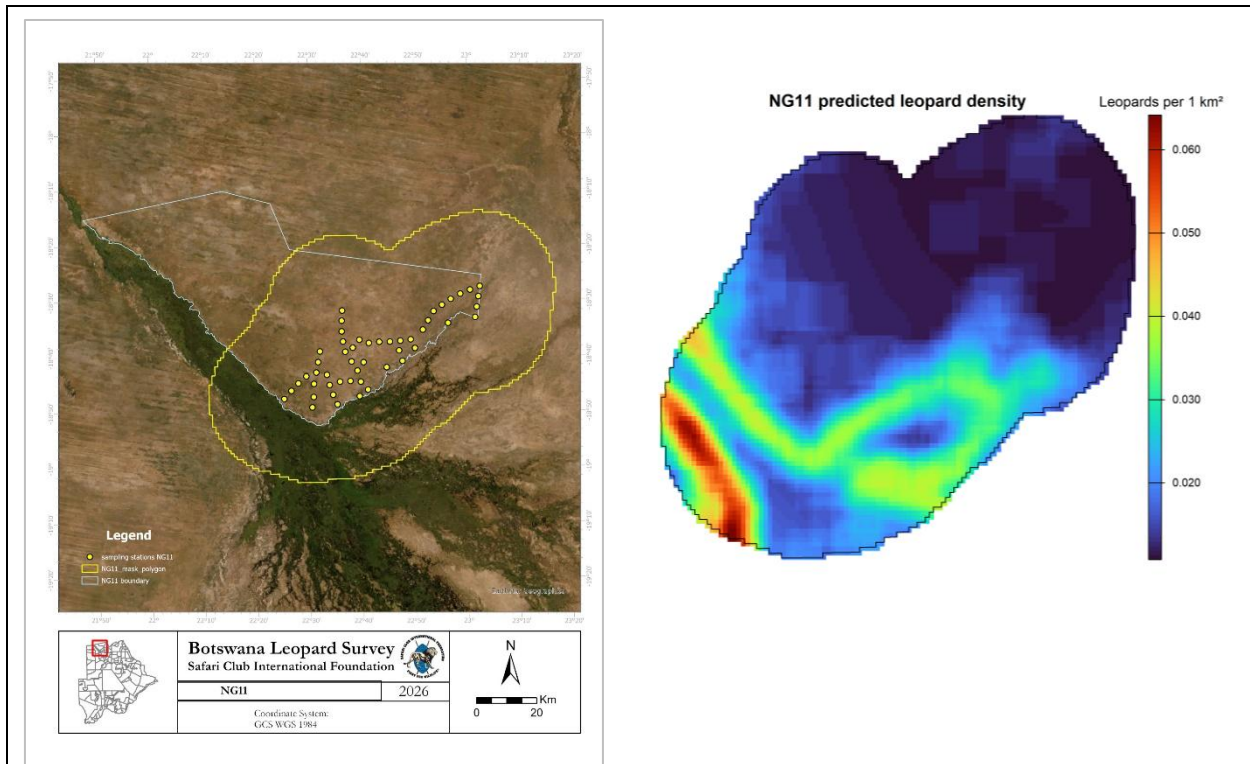


Male NG3_M03



NG11 – HUNTING CONCESSION



**NG11****LEOPARD DENSITY ESTIMATES****Total****D = 0.65 leopards/100 km²****Females****D = 0.47 leopards/100 km² 95% CI [0.26; 0.86]****SE 0.15****CV 0.31****Males****D = 0.18 leopards/100 km² 95% CI [0.10; 0.34]****SE 0.06****CV 0.32****SAMPLING****Number of stations****50****Sampling period****60 days****Average distance between stations****2.48 km****Number of leopard detections****20****Number of leopards identified (males, females, unknown)****11 (M: 4, F:11)**

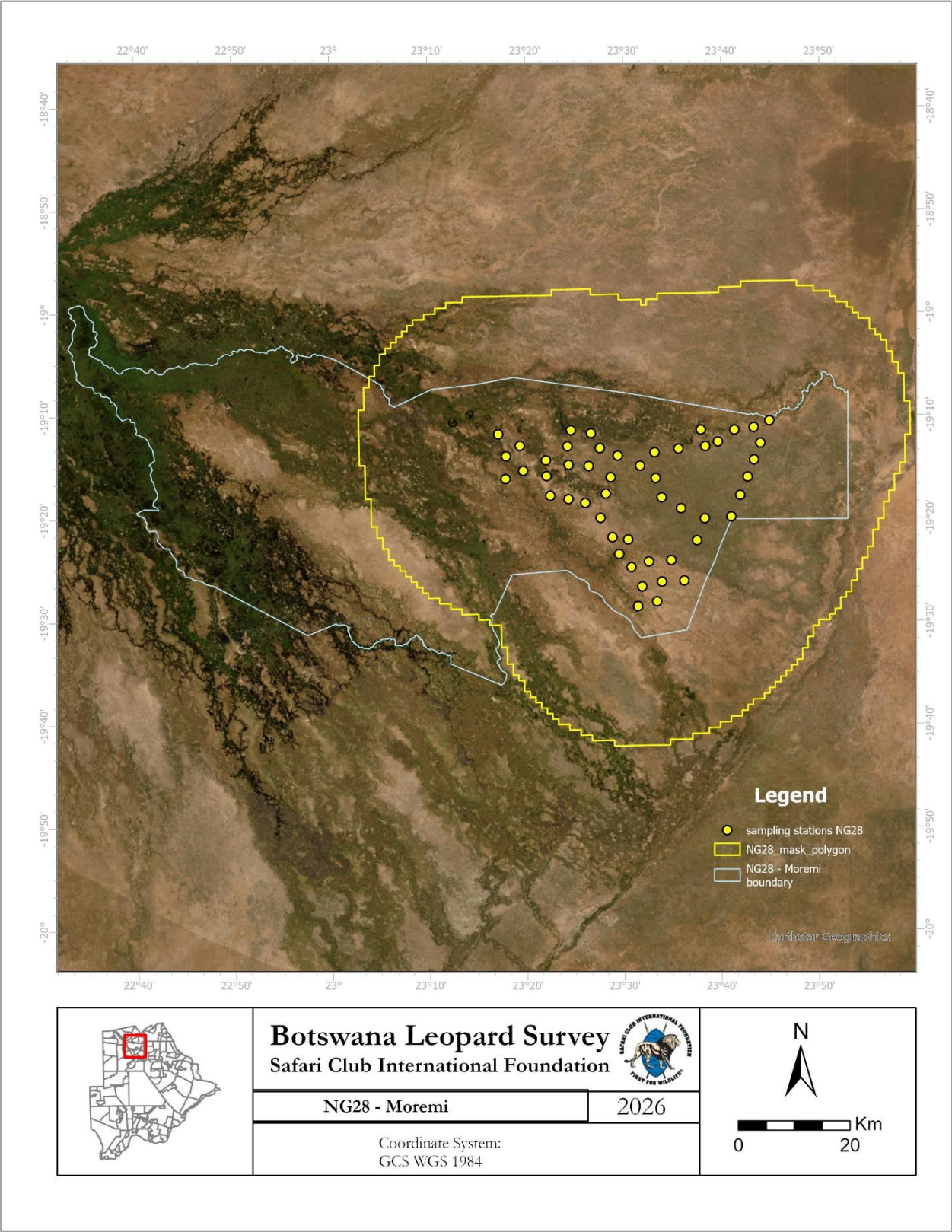
NG11_M01

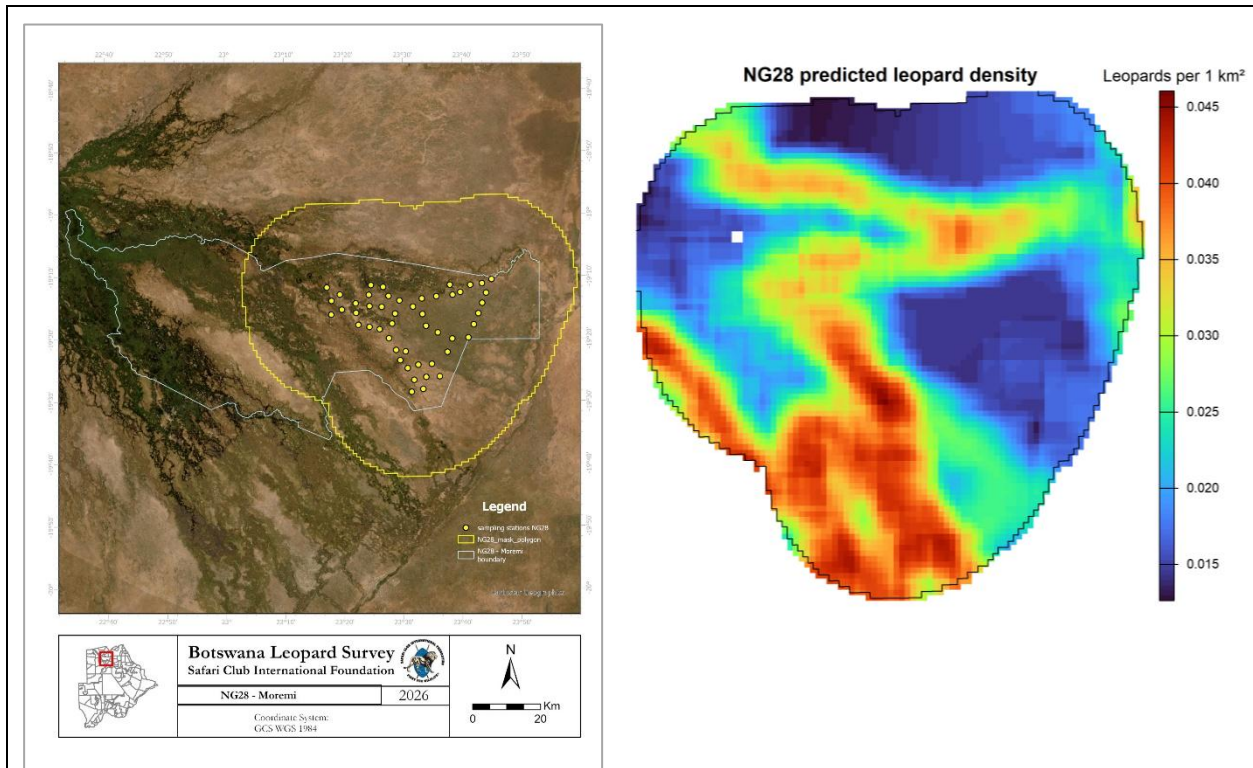


NG11_M03



NG28 – CONSERVATION AREA - MOREMI



**NG28 – Moremi****LEOPARD DENSITY ESTIMATES****Total****D = 2.74 leopards/100 km²****Females****D = 1.97 leopards/100 km²**

95%
CI [1.45; 2.67]

SE 0.31

CV 0.16

Males**D = 0.77 leopards/100 km²**

95%
CI [0.56; 1.05]

SE 0.13

CV 0.16

SAMPLING**Number of stations****50****Sampling period****75 days****Average distance between stations****3.28 km****Number of leopard detections****147****Number of leopards identified (males, females, unknown)****46 (M: 16, F:30)**

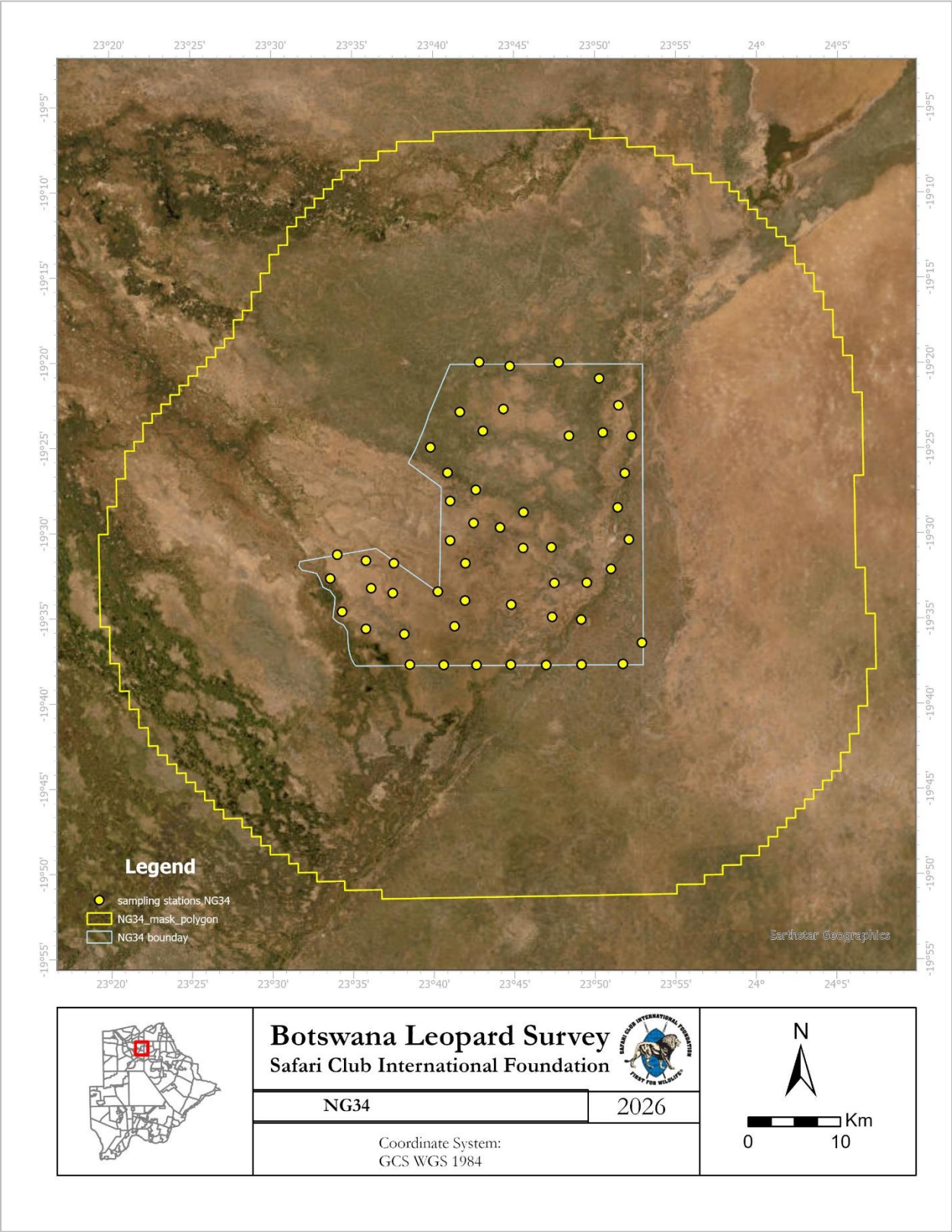
Male NG28_M01

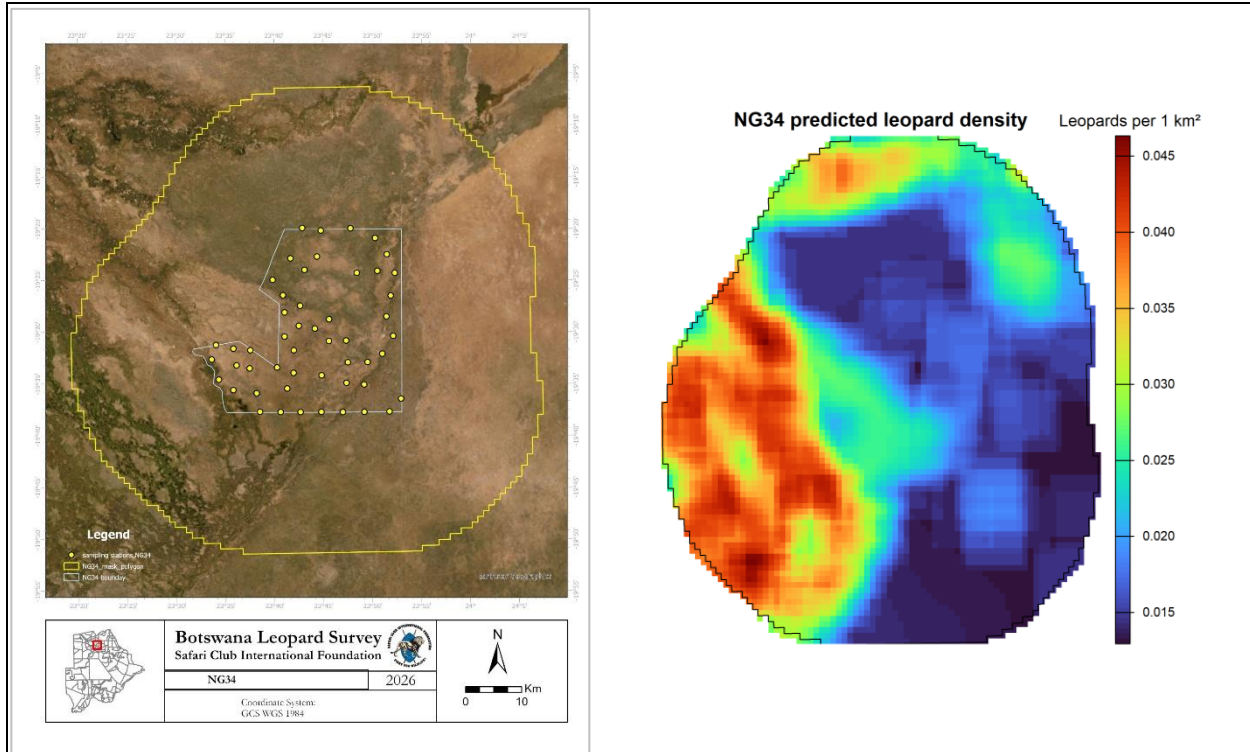


Male NG28_M08



NG34 – COMMUNAL AREA



**NG34****LEOPARD DENSITY ESTIMATES****Total****D = 1.95 leopards/100 km²****Females****D = 1.40 leopards/100 km² 95% CI [0.98; 2.00]****SE 0.26****CV 0.19****Males****D = 0.55 leopards/100 km² 95% CI [0.38; 0.79]****SE 0.10****CV 0.19****SAMPLING****Number of stations****51****Sampling period****85 days****Average distance between stations****3.15 km****Number of leopard detections****76****Number of leopards identified (males, females, unknown)****34 (M: 12, F:20, U:2)**

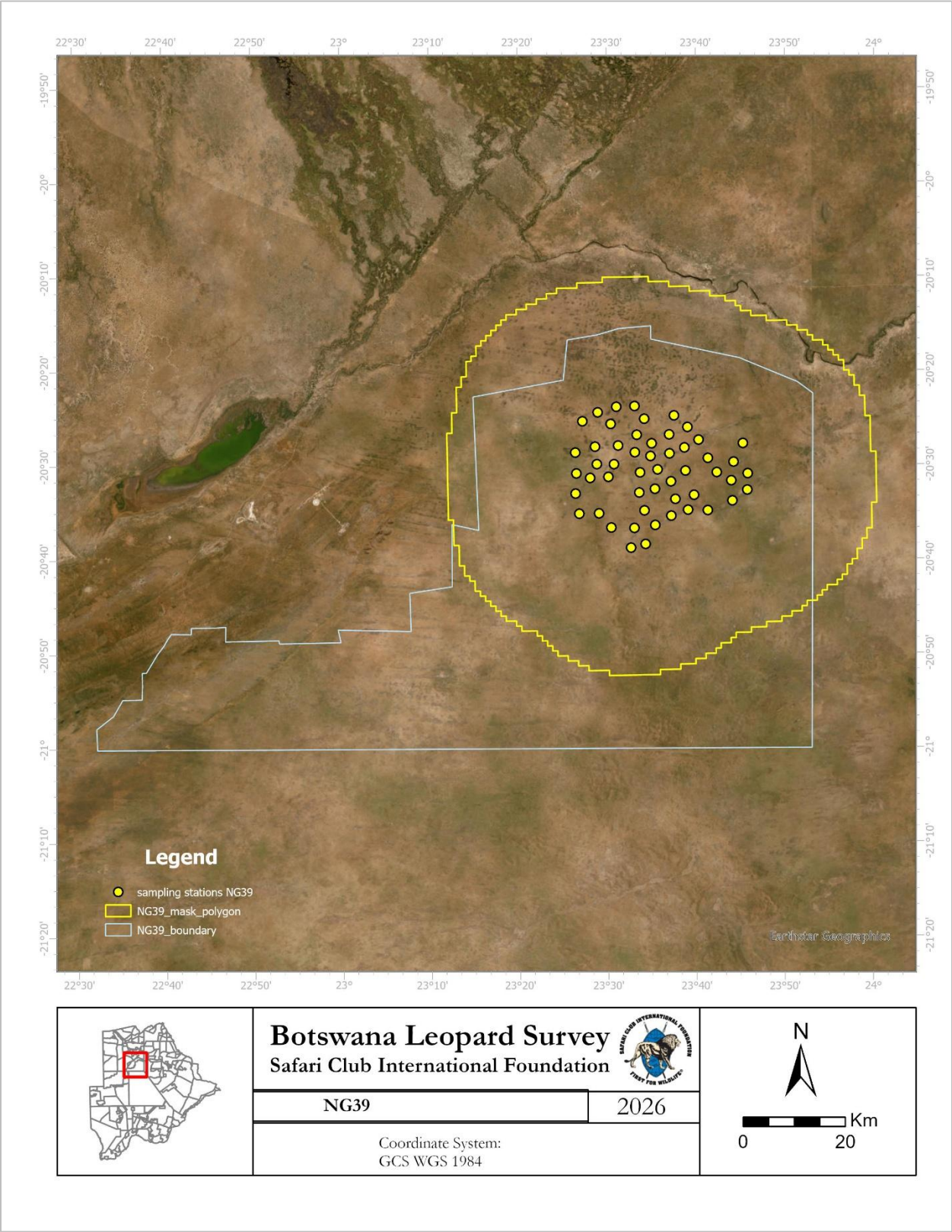
Male NG34_M01

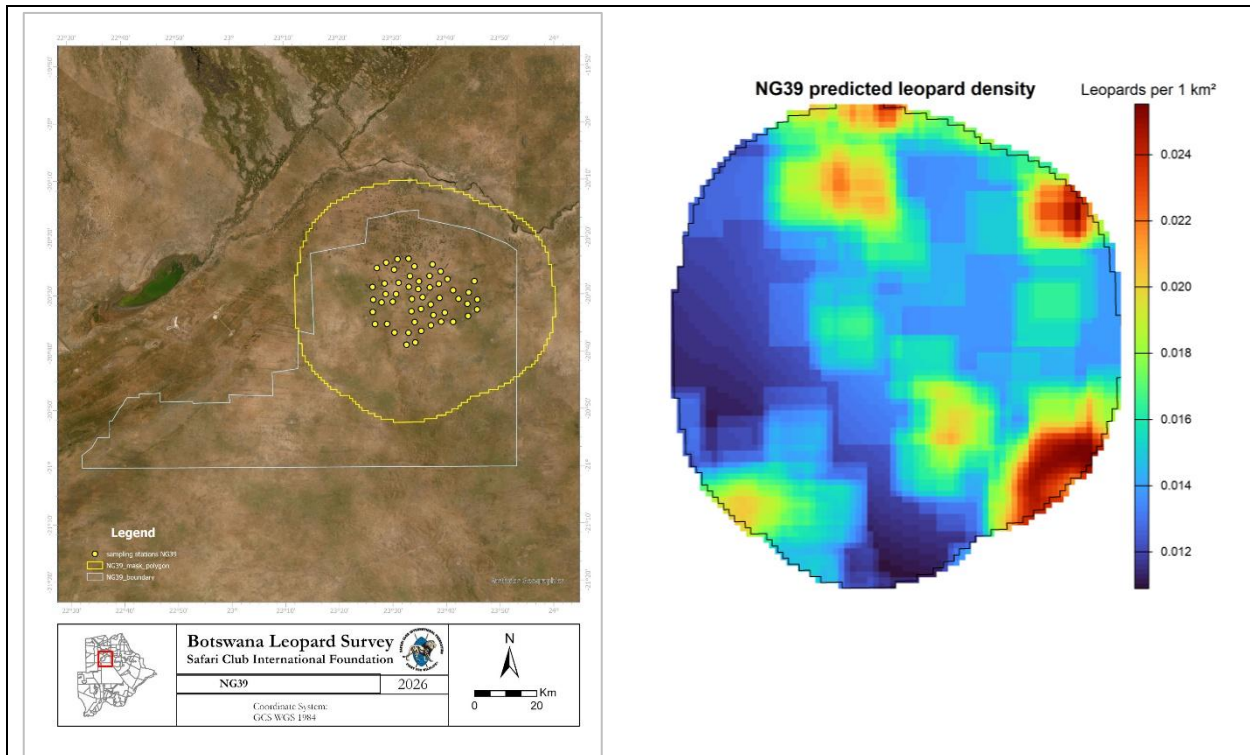


Male NG34_M02



NG39 – WILDLIFE FARM



**NG39****LEOPARD DENSITY ESTIMATES****Total****D = 1.65 leopards/100 km²****Females****D = 1.19 leopards/100 km² 95% CI [0.78; 1.81]****SE 0.26****CV 0.22****Males****D = 0.46 leopards/100 km² 95% CI [0.30; 0.71]****SE 0.10****CV 0.22****SAMPLING****Number of stations****52****Sampling period****70 days****Average distance between stations****3.28 km****Number of leopard detections****96****Number of leopards identified (males, females, unknown)****23 (M: 8, F:15)**

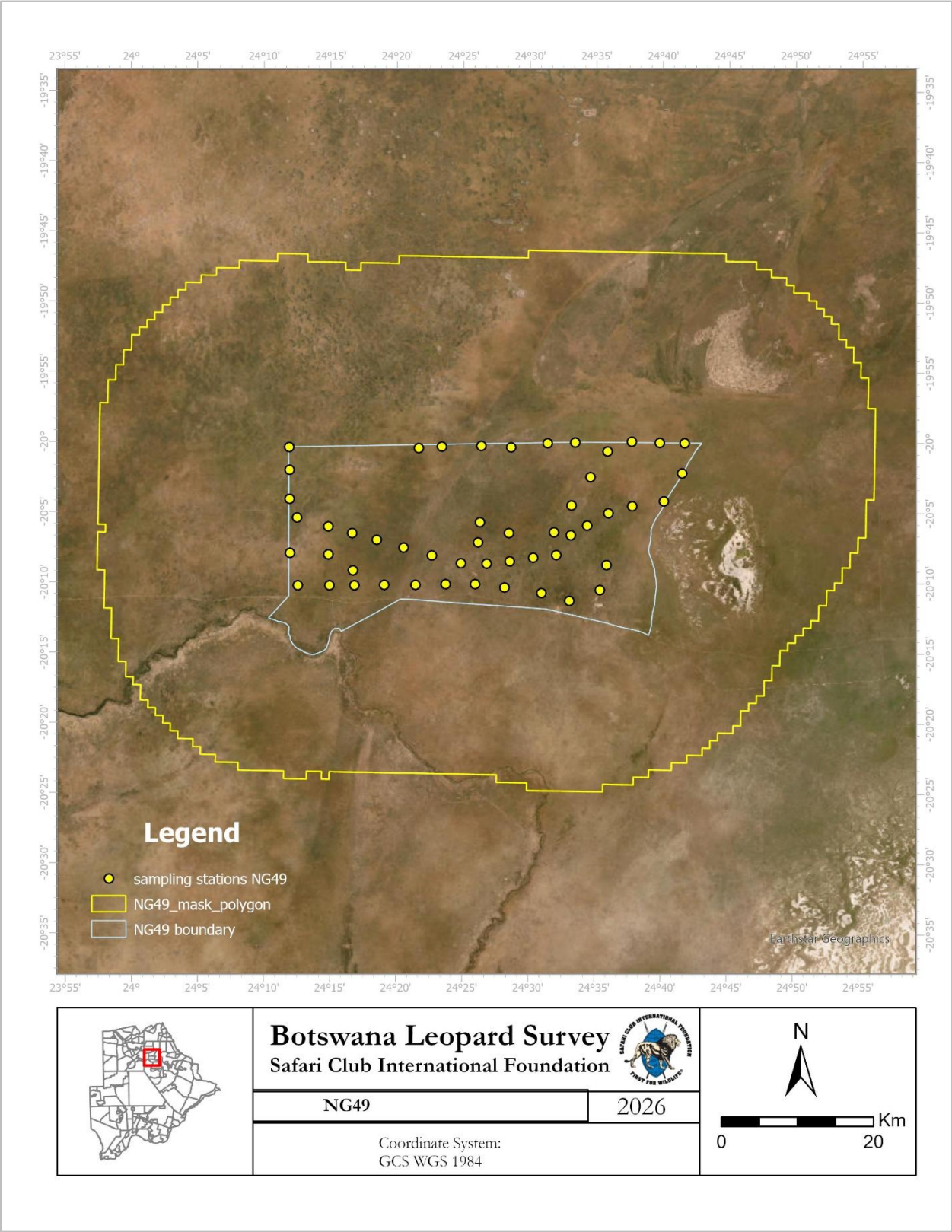
Male NG39_M01

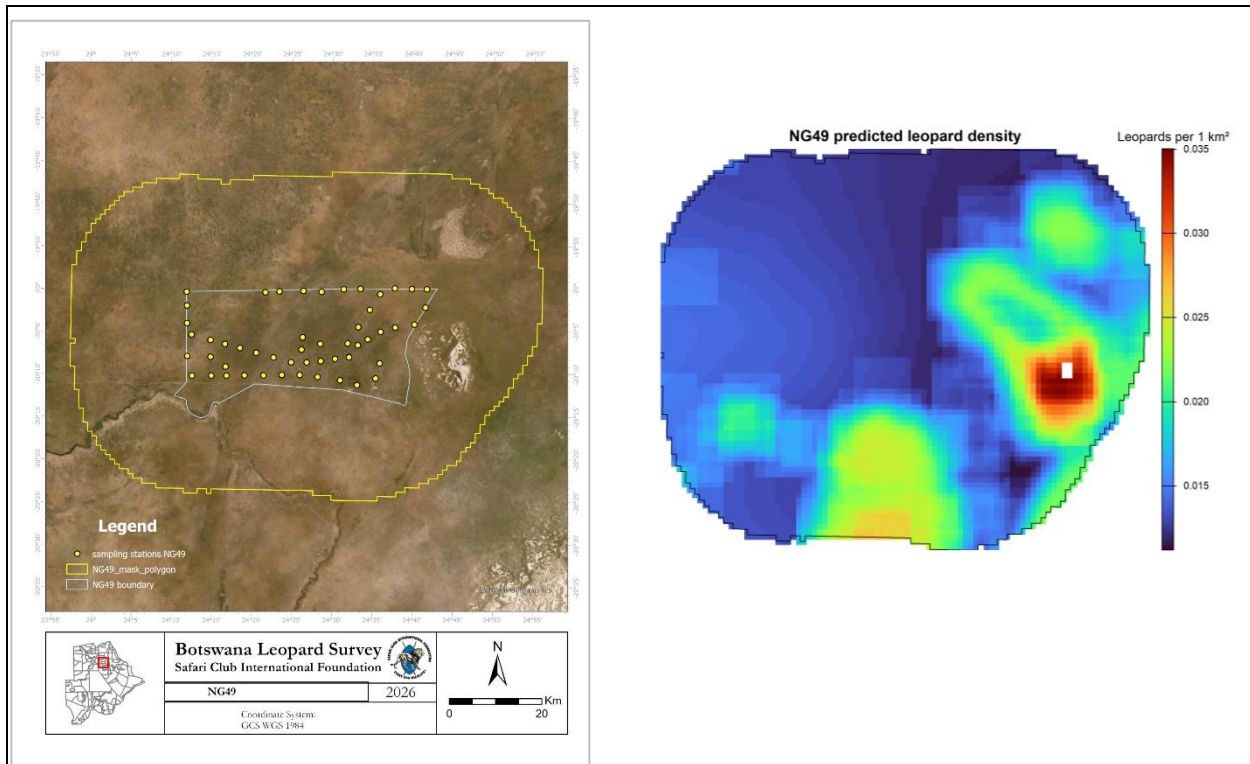


Male NG39_M04



NG49 – COMMUNAL AREA



**NG49****LEOPARD DENSITY ESTIMATES****Total****D = 2.30 leopards/100 km²****Females****D = 1.65 leopards/100 km² 95% CI [1.20; 2.28]****SE 0.27****CV 0.16****Males****D = 0.65 leopards/100 km² 95% CI [0.46; 0.90]****SE 0.11****CV 0.17****SAMPLING****Number of stations****51****Sampling period****93 days****Average distance between stations****3.33 km****Number of leopard detections****214****Number of leopards identified (males, females, unknown)****43 (M: 20, F:22, U:1)**

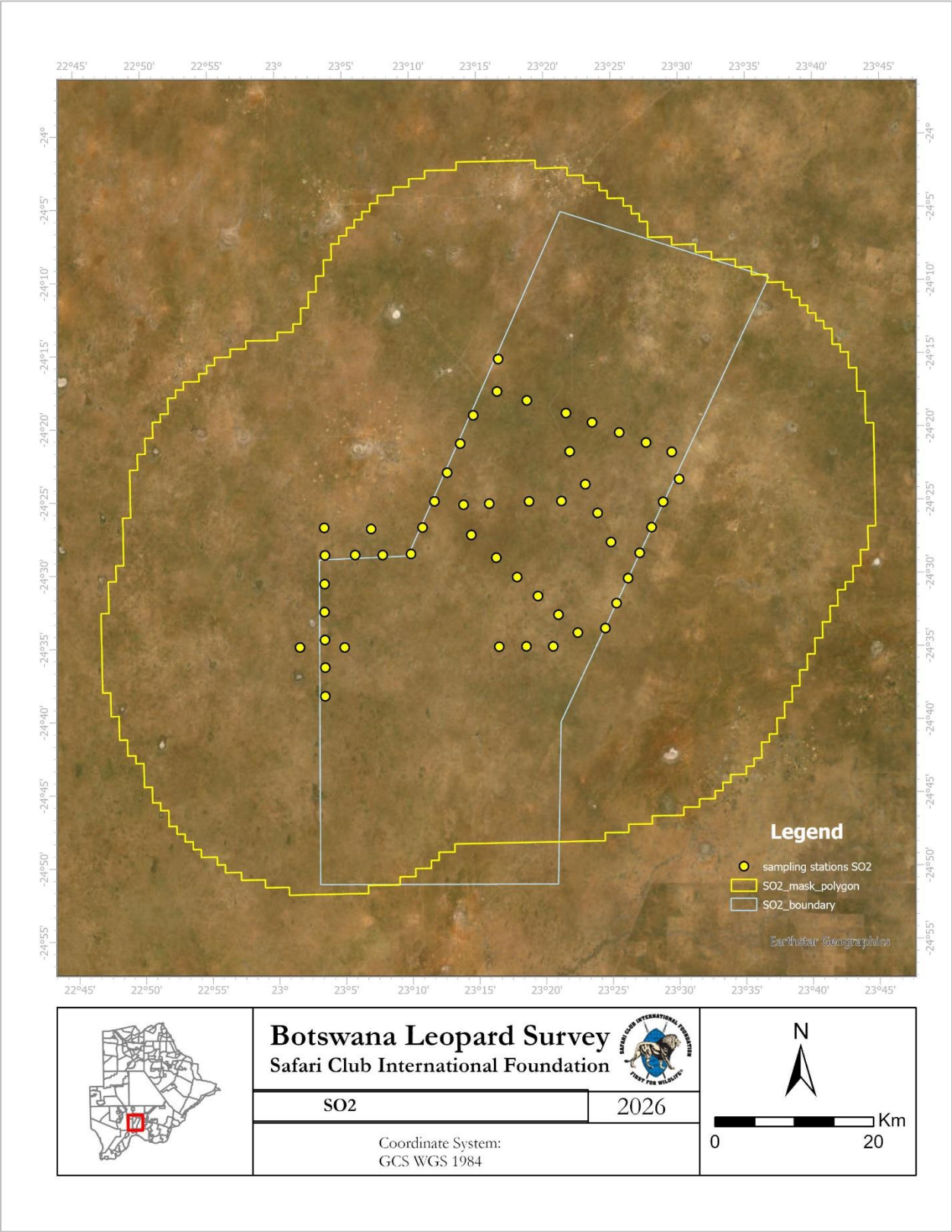
Male NG49_M01

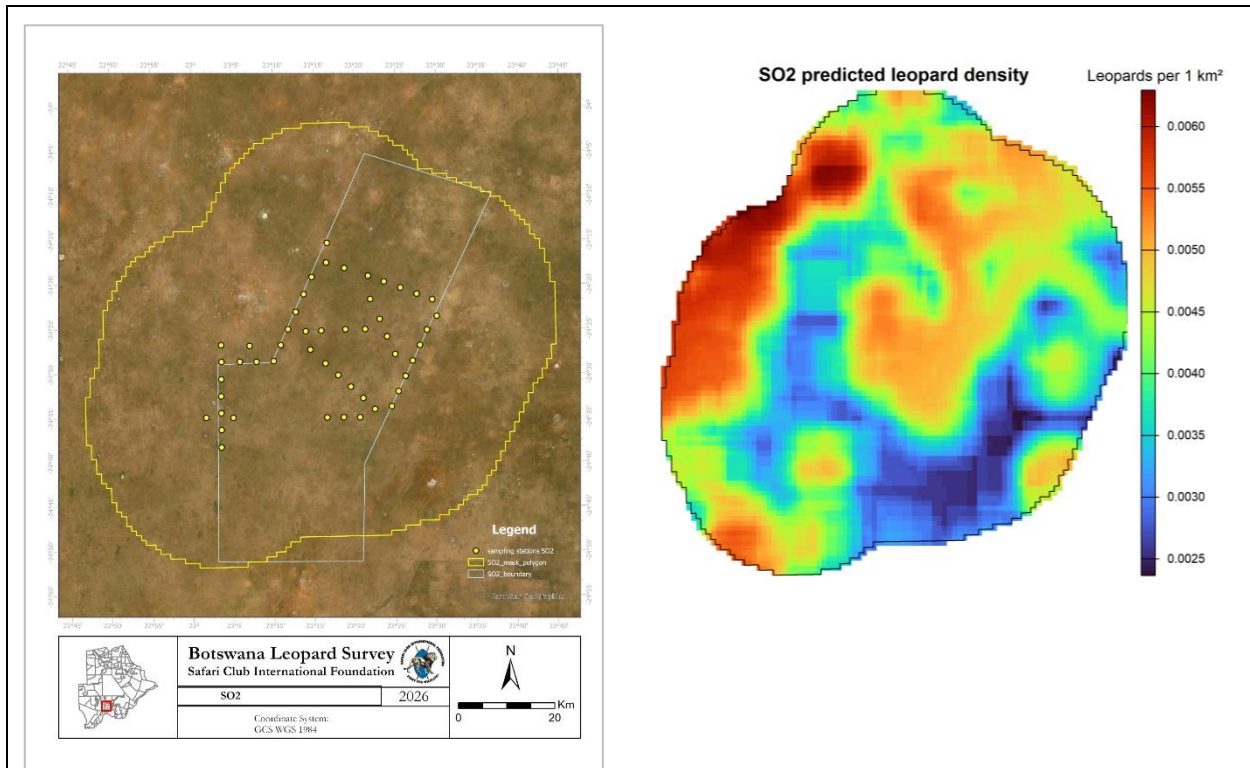


Male NG49_M04



SO2 – WILDLIFE FARM





SO2

LEOPARD DENSITY ESTIMATES

Total

D = 1.18 leopards/100 km²

Females

D = 0.85 leopards/100 km² 95% CI [0.54; 1.34]

SE 0.20

CV 0.23

Males

D = 0.33 leopards/100 km² 95% CI [0.21; 0.53]

SE 0.08

CV 0.24

SAMPLING

Number of stations

50

Sampling period

60 days

Average distance between stations

3.52 km

Number of leopard detections

76

Number of leopards identified (males, females, unknown)

20 (M: 7, F:13)

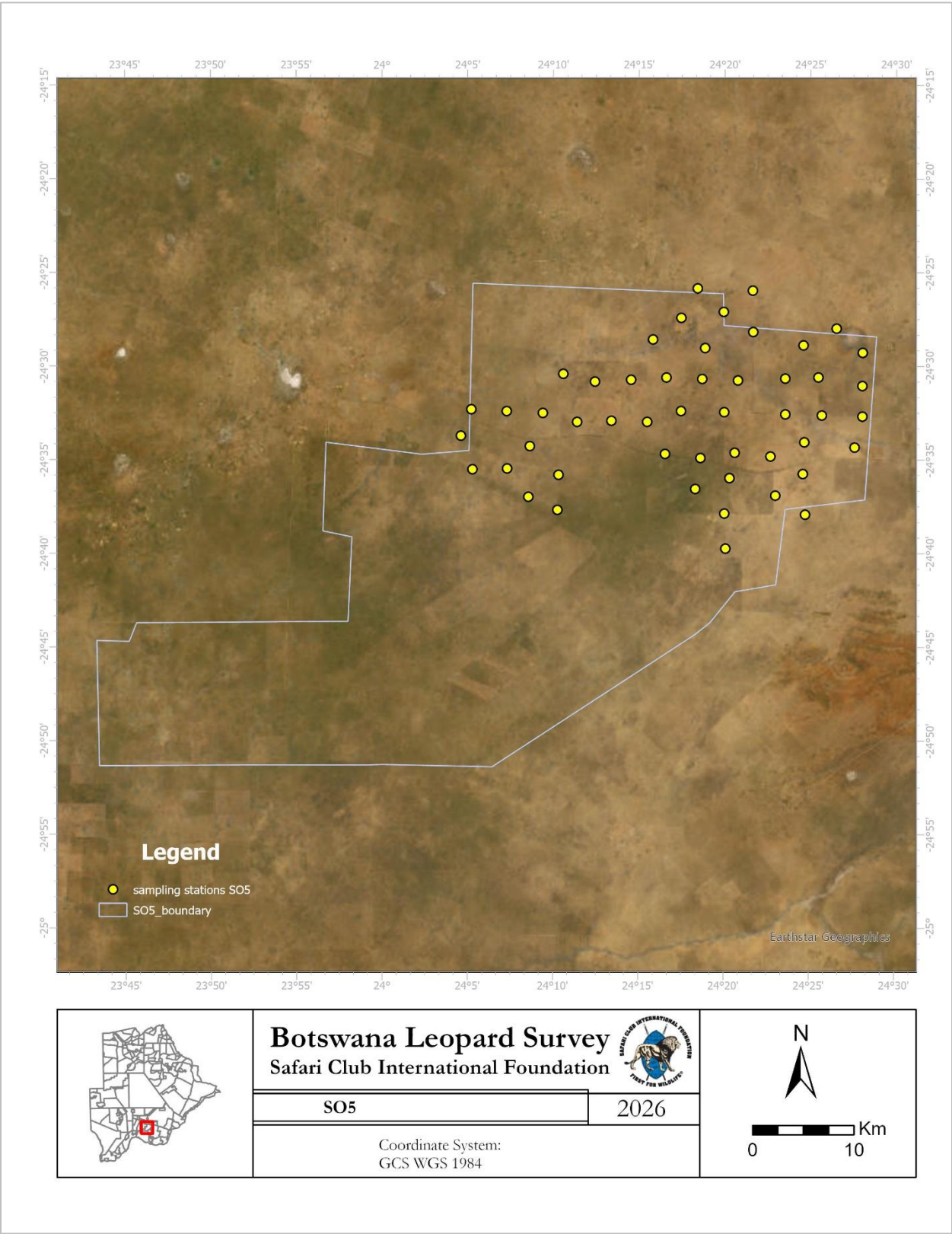
Male SO2_M01

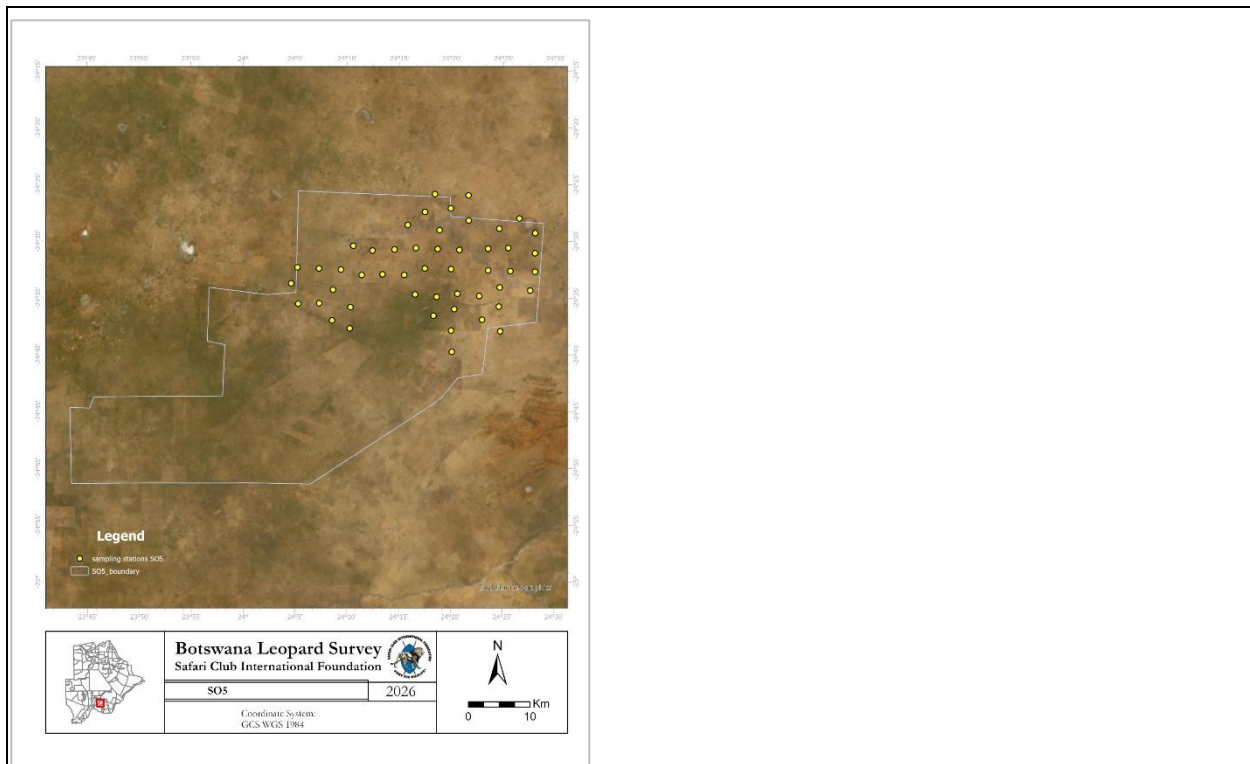


Male SO2_M05



SO5 – WILDLIFE FARM/CATTLE PRODUCTION



**SO5****LEOPARD DENSITY ESTIMATES**

There was a single detection of 1 male leopard in this sampling site.

No density estimation possible.

SAMPLING

Number of stations	50
Sampling period	60 days
Average distance between stations	3.52 km
Number of leopard detections	1
Number of leopards identified (males, females, unknown)	1 (M: 1)

Male SO5_M01 (sole individual detected in SO5)



CONCLUSIONS

This study provides a national-scale assessment of African leopard (*Panthera pardus pardus*) density and distribution across Botswana and, importantly for management, provides direct SECR density estimates for 19 sites distributed across the country. These site-specific estimates, together with their measures of uncertainty, represent the most directly applicable information generated by the study for population management. The national predicted-density and occupancy models complement these estimates by extending the assessment across Botswana and providing information on broader patterns of abundance, distribution, and potential connectivity.

SITE-SPECIFIC LEOPARD DENSITY AND PRECISION

Leopard density varied substantially among the 19 sites, ranging from approximately 0.15 to 2.74 leopards/100 km², an approximately 18-fold difference between the lowest- and highest-density sites. The highest estimates occurred at NG28 (2.74 leopards/100 km²), CKGR (2.67), NG49 (2.30), and NG34 (1.95), whereas CT27 (0.15), KD27 (0.26), and CT18 (0.28) supported the lowest estimated densities.

This pronounced variation is one of the most important findings of the study. It demonstrates that leopard abundance is strongly heterogeneous across Botswana and that a single national density value would not adequately represent local populations. Differences in density are likely to reflect variation in ecological productivity, prey availability, habitat characteristics, competition with other large carnivores, human influence, land use, and mortality.

Low density should not be interpreted as evidence of population decline or poor conservation status. Some landscapes may naturally support relatively few leopards because of low productivity or prey biomass. Conversely, low density in otherwise favorable landscapes could indicate anthropogenic mortality, prey depletion, habitat modification, or other limiting factors. Interpretation of individual sites should therefore consider both the estimated density and the ecological and management context.

The sex-specific estimates provide additional information on population structure. Female densities were consistently higher than male densities, as expected from leopard spatial organization, in which males generally occupy larger home ranges overlapping those of multiple females. Female density is particularly relevant to management because females constitute the reproductive component of the population. Changes in female density through time could therefore provide an important indicator of population response to management and other pressures.

PRECISION AND MANAGEMENT VALUE OF THE DENSITY ESTIMATES

An important strength of the study is that uncertainty was quantified for each density estimate using standard errors, confidence intervals, and coefficients of variation (CV). This allows DWNP to distinguish between estimates and assess their precision for management decisions.

For the purposes of management application, density estimates with CV <30% are considered to have an adequate level of precision to inform management decisions related to leopard quota allocation. Most of the 19 site estimates fall within this category, providing DWNP with a substantial set of directly estimated and reasonably precise measures of leopard abundance from different parts of the country.

The 30% threshold should be viewed as an operational criterion for management, rather than an absolute biological boundary between reliable and unreliable estimates. Precision exists along a continuum, and the consequences of a management decision should determine how uncertainty is treated. Nevertheless, using an explicit threshold provides a transparent mechanism for incorporating statistical uncertainty into management.

Estimates with CV >30% require greater caution and further evaluation before being used as the primary basis for quota allocation. Higher CVs generally occurred at sites with relatively few detections and identified individuals. In these cases, repeated surveys, increased sampling effort, or additional spatial coverage could improve precision. Where management decisions must be made before additional information becomes available, greater uncertainty should correspond to a more precautionary approach. This distinction provides a practical framework for DWNP where precise estimates can inform management, while imprecise estimates identify where additional information is needed.

APPLICATION TO QUOTA SETTING AND ADAPTIVE MANAGEMENT

The availability of direct density estimates across 19 sites creates an opportunity to strengthen the biological basis of leopard quota allocation in Botswana. Rather than assuming similar leopard abundance across management areas, quotas can reflect measured differences in site-specific population density and the confidence associated with those estimates.

Density estimates should not be converted into a proportional harvest quota. Sustainable offtake depends on additional factors, including the geographic extent of the population, sex structure, previous harvest, problem-animal removals and other sources of human-caused mortality, habitat conditions, connectivity with surrounding populations, and population trend. The SECR estimates should therefore provide the population-abundance component of a broader quota-setting framework. Where a site-specific SECR estimate has CV <30%, and the sampled landscape is representative of the area to which management

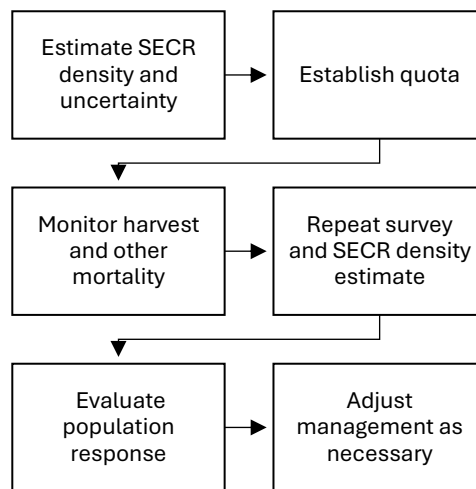
decisions will be applied, the density estimate can provide the primary quantitative measure of local leopard abundance for consideration in quota setting.

Female density warrants particular consideration. Maintaining the reproductive component of the population is fundamental to long-term population persistence, and changes in female density could provide an early indication of demographic effects that may not immediately be evident from total density alone.

The greatest value of the SECR estimates will come from incorporating them into an adaptive management system. The present survey establishes the baseline, while repeated surveys provide the feedback necessary to evaluate the effects of management. If density remains stable under an established level of offtake, this provides evidence consistent with the management regime maintaining population abundance. Conversely, a sustained decline in total or female density should trigger review of harvest levels and investigation of other possible causes.

A PRACTICAL MANAGEMENT CYCLE

For DWNP a practical management cycle would be:



Under this framework, uncertainty becomes an explicit part of decision-making. Sites with precise estimates can support management decisions with greater confidence, whereas sites with higher uncertainty receive additional monitoring or more precautionary management.

NATIONAL PREDICTED-DENSITY SURFACE

The national density model complements the site-specific SECR estimates by extending inference across Botswana. It provides a continuous representation of expected spatial variation in leopard density and therefore places the 19 directly sampled populations within a broader national context.

The density surface indicates substantial geographic variation in predicted abundance, with areas of relatively high predicted density concentrated particularly in portions of northern and northwestern Botswana, together with localized areas elsewhere, while extensive areas of the country are predicted to support lower densities.

For DWNP, this map provides several important applications. It can help identify potential population strongholds, broad gradients in leopard abundance, areas requiring particular conservation attention, and priority locations for additional camera-trap surveys. It also provides information for regions where contemporary direct density estimates are currently unavailable.

An important distinction must nevertheless be maintained between site-specific SECR estimates and national predicted densities. The SECR estimates are based directly on spatial encounter histories of individually identified leopards at surveyed sites. The national surface represents model-based predictions derived from relationships between density and landscape characteristics.

Consequently, where an adequately precise direct SECR estimate is available, that estimate should be given greater weight for local management decisions. The national density surface is most appropriately used for strategic planning, spatial prioritization, and directing future surveys, rather than as a substitute for contemporary local population estimates.

The national map is particularly valuable in an adaptive monitoring framework because it can help DWNP identify where the next surveys will provide the greatest management benefit. Over time, targeted surveys in currently unsampled areas can expand the geographic network of direct density estimates and improve understanding of leopard abundance across Botswana.

OCCUPANCY, DISTRIBUTION, AND CONNECTIVITY

The national occupancy model provides information that cannot be obtained from density alone. Whereas density describes the expected number of leopards per unit area, occupancy describes the probability that leopards occur or use a particular landscape.

The occupancy surface indicates that leopards remain broadly distributed across Botswana, although probability of occurrence varies geographically. This broad distribution is an important conservation finding because it suggests that leopard populations are not restricted to isolated high-density areas.

Density and occupancy should therefore be interpreted as complementary rather than interchangeable measures. High-density areas identify landscapes where leopard abundance is concentrated and which may function as population strongholds. Occupied landscapes with lower density may nevertheless be important because they contribute to population continuity and potentially facilitate dispersal between higher-density areas.

Maintaining these connections is particularly important for a wide-ranging carnivore. Dispersal among populations contributes to demographic exchange, recolonization, and genetic connectivity. Conservation planning should therefore not focus exclusively on areas supporting the highest densities but should also consider the broader landscape required to maintain a connected national population.

For management purposes, the two national surfaces answer different questions:

- Density → Where are leopard populations concentrated?
- Occupancy → Where are leopards distributed and where may connectivity be maintained?

Together with the direct SECR estimates, these maps provide DWNP with complementary information at local, regional, and national scales.

IMPLICATIONS FOR CONSERVATION AND ADAPTIVE LEOPARD MANAGEMENT

The principal management value of this study is the establishment of direct SECR density estimates for 19 sites across Botswana, accompanied by explicit measures of precision. These estimates provide a quantitative foundation for developing a more spatially explicit and adaptive approach to leopard conservation and sustainable use.

For quota allocation, SECR estimates with CV <30% provide a level of uncertainty considered adequate to inform management decisions, provided that the survey is representative of the relevant management area

and the estimate is considered together with female density, previous harvest, other human-caused mortality, connectivity, and available evidence of population trend.

Sites with CV >30% should receive additional evaluation before their density estimates are used as the primary basis for quota allocation. These sites provide important information on leopard status, but greater uncertainty warrants additional monitoring or a more precautionary management approach.

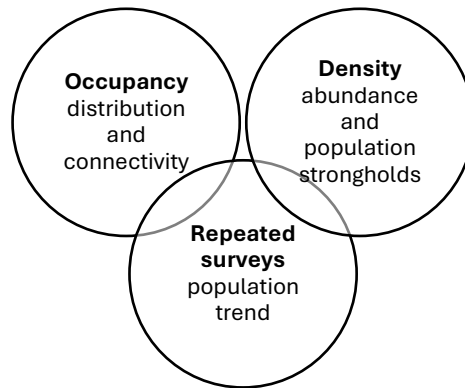
The national density and occupancy maps serve complementary management functions. The density map identifies broad patterns of abundance, potential population strongholds, and priority areas for additional surveys, while the occupancy map provides information on national distribution and landscapes potentially important for connectivity. Neither should replace adequately precise direct density estimates where these are available.

Most importantly, the present survey establishes a national baseline. A single density estimate describes population status at one point in time; repeated estimates provide the information necessary to determine whether populations are stable, increasing, or declining. DWNP could therefore maintain a representative network of monitoring sites encompassing important hunting areas, high-density populations, low-density populations, and landscapes of particular conservation or connectivity importance.

Overall, the results indicate that leopards remain widely distributed but occur at markedly different densities across Botswana. The 19 direct density estimates, particularly those with CV <30% provide, the strongest quantitative basis currently available for spatially explicit management, while the density and occupancy surfaces provide the national context needed to identify strongholds, maintain connectivity, and prioritize future monitoring. Integrating these components within an adaptive management framework would allow quota decisions to be based on measured abundance, uncertainty to determine the appropriate level of precaution, and management to be adjusted over time according to observed population responses.

MANAGEMENT FRAMEWORK

The principal outputs of this study can therefore be viewed as three complementary components of national leopard management:



The resulting hierarchy of information derived from these outputs provides a practical framework for DWNP:

- SECR density with CV <30% → primary population information for local management and quota decisions
- SECR density with CV >30% → additional evaluation, monitoring, and greater precaution
- National density surface → population strongholds, spatial planning, and survey prioritization
- Occupancy surface → distribution and potential connectivity
- Repeated SECR surveys → population trend and evaluation of management outcomes

Together, these components provide DWNP with a framework for moving from a one-time national assessment and quota allocation toward adaptive leopard management. Repeated monitoring, combined with information on prey populations, habitat change, legal harvest, problem-animal removals, illegal mortality, and human–wildlife conflict, would allow changes in leopard populations to be detected, their likely causes investigated, and management responses evaluated.

Overall, this study indicates that leopards remain broadly distributed across Botswana, and that their abundance varies markedly among landscapes. This combination of broad occurrence and strong spatial variation is the central conservation finding of the national survey. Maintaining high-density population strongholds while preserving connectivity through the broader occupied landscape, and monitoring both through time, should therefore form the foundation of long-term leopard conservation and management in Botswana.

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APPENDIX A. MODELING PROCESS FOR ESTIMATING LEOPARD DENSITY

GENERAL CONCEPTS

Estimating how many leopards live in a given area is challenging because leopards are elusive, mostly nocturnal, and occur at low densities. SCIF's scientists used a method called Spatially Explicit Capture-Recapture (SECR) modeling to turn camera trap photos into reliable estimates of leopard density.

Why SECR modeling is the right approach

SECR modeling provides a scientifically robust estimate of leopard density, even when not all animals are seen. This is critical for conservation and management decisions, such as setting sustainable hunting quotas or monitoring population trends over time. Here's how the process works in simple terms:

Collecting the Data: Camera Traps

SCIF researchers place motion-activated cameras across the study area. The size of the area where the cameras are deployed must be big enough to overlap with the home range of multiple leopards. These cameras take photos whenever a leopard passes by. Leopards have unique spot patterns—like fingerprints—so each individual can be identified from the images.

Captures and Recaptures

Every time a leopard is photographed, it's considered a *capture*. If the same leopard is photographed again—at the same camera or a different one—that's a *recapture*. Over time, researchers build a detection history for each individual leopard, showing where and how often it was photographed.

Adding the Spatial Element

This is where SECR differs from simpler methods. Instead of just counting how many times animals are seen, SECR also considers where each leopard was detected. The model assumes each leopard has a *home range center* (like the center of its territory), and the chance of detecting that leopard decreases the farther it is from that center.

Estimating Detection Probability

Not every leopard in the area will be photographed. SECR models estimate the probability of detecting a leopard based on distance from its home range center and how often it moves around. This helps account for animals that were present but never photographed.

Defining the Study Area

Rather than arbitrarily drawing boundaries, SECR models use the spatial detection data to estimate the effective area that was actually sampled. This avoids over- or underestimating density.

Estimating Density

By combining the number of identified leopards, how often they were detected, and where they were detected, the SECR model calculates how many leopards are likely to exist per unit area (e.g., per 100 square kilometers).

SPATIALLY EXPLICIT CAPTURE–RECAPTURE MODELING AND LANDSCAPE-LEVEL DENSITY ANALYSIS

Spatially explicit capture–recapture (SECR) models provide a robust framework for estimating animal density by explicitly incorporating the spatial locations of individual detections and detectors into the analysis.

Unlike traditional non-spatial capture–recapture approaches, which first estimate abundance and subsequently require an estimate of the effective sampling area to derive density, SECR models estimate density directly by jointly modeling the spatial distribution of individual activity centers and the detection process as a function of distance between activity centers and detectors (Efford et al. 2009; Royle et al. 2014). This approach avoids the need to define an effective sampling area using ad hoc boundary buffers and thereby reduces an important potential source of bias in density estimation. SECR methods are therefore particularly well suited to camera-trap studies of individually identifiable species such as leopards.

SECR models comprise two linked components. The first is a spatial point-process model describing the distribution of individual activity centers within a predefined state space, typically represented by a habitat mask that encompasses the detector array and extends sufficiently beyond its boundaries. This extension allows individuals whose activity centers occur outside the detector array, but whose movements bring them within detection range of cameras, to contribute appropriately to the likelihood. The second component is a detection model that describes how the probability of detecting an individual declines with increasing distance between its activity center and a detector. Under a commonly used half-normal detection function, this relationship is characterized by the baseline detection parameter (g_0) and spatial scale parameter (σ). The parameter g_0 represents detection probability at zero distance between the individual's activity center and the detector under a Bernoulli detection model, whereas σ determines the rate at which detection probability declines with distance and is therefore related to the spatial scale of animal movements.

By jointly modeling the spatial distribution of activity centers and the distance-dependent detection process, SECR models estimate density while accounting for imperfect detection and variation in the spatial

relationship between animals and detectors. Provided that the underlying assumptions are adequately met, this likelihood-based framework provides a statistically rigorous means of estimating population density and associated uncertainty.

All analyses were conducted in R version 4.5.3 (R Core Team 2026). We used two complementary spatial capture–recapture approaches to estimate leopard density across the surveyed sites. First, we implemented a multi-session SECR analysis using the R package *secr* v5.4.2 (Efford et al. 2026). The multi-session framework allowed data from multiple survey sites to be analyzed jointly while permitting selected model parameters to vary among sites and according to other hypothesized sources of variation.

We first obtained an estimate of the spatial scale parameter σ from the multi-session analysis and used this value to define the extent of the state space. For each survey site, the habitat mask extended approximately 4σ beyond the outermost detectors. This buffer was intended to ensure that the state space was sufficiently large that individuals with activity centers outside the detector array but with a non-negligible probability of detection were represented in the likelihood (Efford 2026). Areas considered unavailable to leopards, where applicable, were excluded from the habitat mask.

We developed a candidate set of SECR models representing alternative hypotheses regarding variation in leopard density and the detection process. Attention was given to both trap-level and individual-level sources of heterogeneity that could influence detectability and potentially bias density estimates if not adequately modeled. Detection was described using g_0 and σ , and we evaluated models in which these parameters varied by sex to account for expected differences in detectability and movement between male and female leopards. Because male leopards generally range over larger areas than females, sex-specific effects on σ were considered particularly relevant. We also evaluated behavioral responses at the detector level to determine whether an individual's detection probability at a camera station changed following its initial detection there.

In addition to these observed sources of variation, we evaluated unobserved individual heterogeneity in detection that could not be explained by sex or measured detector-level effects. Such heterogeneity could arise from differences among individuals in movement behavior, reproductive status, dispersal, territorial status, or other unmeasured characteristics. We accounted for this possibility using two-class finite-mixture models in which individuals were assigned probabilistically to one of two latent classes representing otherwise unobserved differences in detectability. Latent mixture class was allowed to influence both g_0 and σ , thereby permitting the classes to differ in both baseline detectability and the spatial scale of detection.

The resulting candidate model set evaluated alternative effects of site, sex, behavioral response, and latent individual heterogeneity on density (D) and/or detection parameters g_0 and σ . Candidate models were

compared using Akaike's Information Criterion corrected for small sample size (AICc). Relative model support was assessed from differences in AICc and associated model weights, together with model parsimony and biological interpretability. Site-specific leopard density estimates and associated measures of uncertainty were subsequently derived from the best-supported SECR model.

As a complementary analysis, we estimated leopard density using SPACECAP v1.1.0 (Gopalaswamy et al. 2012), a Bayesian spatial capture–recapture framework that estimates population density while explicitly modeling the locations of latent individual activity centers. SPACECAP additionally allowed us to characterize spatial variation in the posterior distribution of activity centers within the state space, providing a spatially explicit representation of expected leopard density for each survey site. The state space was discretized using 1×1 km grid cells.

SPACECAP models were fitted using a half-normal detection function and a Bernoulli encounter model, with a behavioral trap-response effect included to account for potential changes in detection probability following an individual's initial detection. Markov chain Monte Carlo (MCMC) sampling was conducted for 100,000 iterations, with the first 25,000 discarded as burn-in and every tenth subsequent iteration retained. Data augmentation was set to five times the number of individually identified leopards detected at each survey site. Model convergence and adequacy of MCMC sampling were evaluated using the diagnostic outputs available in SPACECAP.

Both the maximum-likelihood *secr* analysis and Bayesian SPACECAP analysis therefore used spatial capture–recapture formulations that explicitly accounted for the spatial arrangement of detectors, the locations of individual detections, and latent activity centers. Whereas the *secr* analysis was used to obtain site-specific density estimates and associated uncertainty, the spatial output from SPACECAP was used to characterize within-site variation in expected leopard density. SPACECAP-derived density values were extracted at camera-station locations and used as the response variable in subsequent landscape-level analyses.

To evaluate landscape-level correlates of leopard density, we related station-level SPACECAP-derived density estimates to environmental and anthropogenic covariates using generalized linear models (GLMs) with a gamma error distribution and an appropriate positive-valued link function. Prior to model fitting, candidate covariates were evaluated to identify the most biologically relevant spatial scale of effect and to reduce multicollinearity among predictors. We then fitted a null model, a global model containing all retained covariates, and a candidate set comprising all biologically plausible combinations of those covariates.

Support for competing models was evaluated using an information-theoretic approach based on Akaike's Information Criterion corrected for small sample size (AICc), implemented using the R package MuMIn

v1.48.19 (Bartoń 2026). Models were evaluated according to their AICc values, relative support, parsimony, and ecological interpretability. The best-supported model was subsequently used to generate a national predictive surface of leopard density.

We generated the national density surface by applying the fitted relationship from the selected GLM to spatially continuous raster layers representing the retained predictor variables at their selected scales of effect. To propagate uncertainty in the fitted regression coefficients into predictions of abundance, we used a parametric simulation approach. The estimated regression coefficients β (beta), their standard errors, and the estimated covariance among coefficients were used to parameterize a multivariate normal distribution. We then generated 1,000 realizations of the coefficient vector from this distribution. Each realization was applied to the national covariate rasters to produce a predicted leopard-density surface, from which total abundance was calculated by integrating predicted density across the modeled area.

The distribution of the resulting 1,000 abundance estimates was used to characterize uncertainty in national abundance. The 2.5th and 97.5th percentiles of this distribution were taken as the lower and upper bounds of an approximate 95% uncertainty interval. This procedure propagates uncertainty associated with estimation of the GLM coefficients into the national abundance estimate, although it does not incorporate all possible sources of uncertainty, including uncertainty in the underlying SPACECAP density estimates, covariate surfaces, model structure, or extrapolation beyond the environmental conditions represented by the surveyed sites.

APPENDIX B. MODELING PROCESS FOR ESTIMATING LEOPARD OCCUPANCY

We estimated detection and occupancy for leopards using single-species, single-season occupancy models in R (R Core Team 2026) with the package *unmarked* (Fiske and Chandler 2011). Occupancy was estimated from independent leopard detections at camera stations. Additionally, we evaluated the effects of the same spatial scales of the site covariates that were selected for the top density model on leopard occupancy. Detection probability was modeled as a function of cumulative weekly precipitation, NDVI, and weekly minimum and maximum temperatures.

Camera trap detections were organized into detection/non-detection histories across repeated sampling occasions, with each sampling occasion consisting of 7 days, allowing us to explicitly account for imperfect detection while estimating the probability that a leopard occupied a site. Occupancy (ψ) and detection probability (p) were modeled as separate processes, accounting for imperfect leopard detection. We used a sequential-by-sub-modeling process for modeling detection while holding occupancy constant (Morin et al. 2020).

After selecting the most parsimonious detection sub-model, we held it constant while modeling different combinations of sub-models for occupancy. Models were ranked, selected, and evaluated using AIC with the 'modSel' function in the *unmarked* R package (Burnham and Anderson 2002, Fiske and Chandler 2011). We performed model-averaging using informative models within our candidate set of occupancy models. Models that contributed 90% of the cumulative candidate model set weight were used for prediction. Model-averaging is a technique that is normally used when model selection uncertainty occurs and/or for predictive analysis (Arnold 2010). The final raster represented model-averaged leopard occupancy probability at a 1km resolution across Botswana.

Occupancy for each grid cell was quantified using the top model-specific beta estimate and respective covariate measurement for each grid cell throughout the country. We assessed in-sample discriminatory performance by calculating the area under the receiver operating characteristic curve using the *pROC* package (Robin et al. 2011), comparing model-averaged predictions with observed leopard detection–no detection at surveyed stations.

APPENDIX C. EXTENDED SAMPLING PERIOD, POPULATION CLOSURE, AND PRECISION OF DENSITY ESTIMATES

Camera-trap sampling periods in this study were extended where necessary to obtain sufficient leopard detections and spatial recaptures for reliable spatially explicit capture–recapture (SECR) estimation. Although capture–recapture models assume that the sampled population is closed during data collection, strict demographic closure is rarely achieved in natural populations because individuals may die, disperse, immigrate, or be recruited during the survey. Increasing survey duration therefore creates an important trade-off between improving the precision of density estimates and increasing the potential for bias associated with violation of population closure.

This trade-off is particularly relevant for rare, elusive, and wide-ranging species such as leopards. SECR models depend not only on detecting individuals, but also on obtaining sufficient repeated detections, including detections of the same individuals at different camera stations, to estimate detection probability and the spatial scale of movement. Short sampling periods may therefore produce datasets with too few individuals or spatial recaptures to estimate density precisely. Dupont et al. (2019) demonstrated that increasing sampling duration increases both the number of individuals detected and the total number of detections, and that even relatively modest increases in sample size can result in substantial improvements in the precision of SCR estimates. This consideration is particularly important for species characterized by low detection probabilities (e.g. leopards), for which sparse datasets can substantially limit inference.

The benefit of longer sampling periods must, however, be balanced against the increasing probability that individuals enter or leave the sampled population. Under strict closure, the population represented at the beginning and end of a survey is assumed to remain unchanged. Consequently, an estimate derived from a population experiencing substantial turnover may increasingly represent the cumulative set of individuals present at some point during the sampling interval rather than population abundance at a single point in time. Dupont et al. (2019) explicitly evaluated this tension between sampling duration, precision, and closure. Their simulations showed that longer surveys improve precision but can introduce positive bias when demographic turnover becomes sufficiently large.

Importantly, the magnitude of this trade-off depends strongly on the life-history characteristics of the species being studied. Dupont et al. found that longer sampling periods were particularly advantageous for slow-living species: both relative bias and uncertainty in estimated parameter declined as survey duration increased, and closure violations associated with longer surveys had comparatively little effect on estimates. In contrast, species with intermediate or fast life histories experienced progressively greater bias as survey duration increased because demographic turnover occurred rapidly enough for substantial numbers of individuals to enter or leave the population during sampling.

Leopards are relatively long-lived, low-fecundity large carnivores and therefore lie considerably closer to the slow than to the fast end of the life-history continuum considered by Dupont et al. This is relevant to the Botswana surveys because demographic turnover over a period of several months is expected to represent a relatively small proportion of the adult population compared with short-lived, rapidly reproducing species. Extended camera-trap sampling periods have also been used in previous leopard studies, demonstrating that relatively long sampling windows are not unprecedented for this species (Briers-Louw et al., 2023; Hinde et al. 2023, Morris et al., 2021). The results of Dupont et al. therefore provide support for allowing longer sampling periods for species with this general life-history strategy when the additional sampling substantially improves the number of detections and spatial recaptures available for SECR analysis.

The timing of an extended survey is nevertheless important. Dupont et al. found that recruitment was a more important source of positive bias than mortality in their simulations. Surveys overlapping periods of concentrated recruitment produced increases in both bias and uncertainty because newly recruited individuals became available for detection for only part of the sampling period. Thus, increasing the number of distinct individuals detected does not necessarily improve precision if many of those individuals are available for only a short portion of the survey and consequently have few repeat detections. Dupont et al. consequently recommend extending sampling periods as far as practically useful while, where possible, avoiding periods of concentrated recruitment.

For the Botswana leopard surveys, an additional measure reduced the potential influence of recruitment on the SECR estimates. Cubs and dependent or clearly subadult individuals were not included as individuals in the SECR analyses, meaning that juveniles entering the detectable population during the survey did not directly contribute to estimates of adult leopard density. This likely reduced one of the principal mechanisms by which extended sampling periods can violate demographic closure, namely the addition of newly recruited individuals during the sampling period. Dupont et al. (2019) specifically identified recruitment as an important source of positive bias when longer sampling periods overlap periods in which new individuals enter the sampled population. However, the presence of dependent cubs may still indirectly influence the detection process. Females with young cubs can temporarily restrict their movements and spend more time close to den sites, potentially reducing their probability of encountering camera stations or altering the spatial scale of their movements relative to females without dependent young. Thus, although excluding cubs and subadults likely reduced recruitment-related bias in density estimation, reproductive status may still have contributed to heterogeneity in female detection probability and movement during the surveys.

For our surveys, the use of extended sampling periods was therefore considered a deliberate bias–precision trade-off rather than an assumption that population closure was absolute. Shortening surveys solely to strengthen the closure assumption could substantially reduce the number of leopard detections and spatial

recaptures, resulting in high coefficients of variation, wide confidence intervals, unstable detection and movement parameters, or—in particularly sparse datasets—an inability to obtain meaningful density estimates. Conversely, extending sampling indefinitely would progressively increase the probability of demographic turnover and the potential for closure-related bias. The objective was therefore to sample for sufficiently and reasonable long periods to obtain adequate information for precise SECR estimation while keeping the survey short relative to the demographic timescale of a long-lived species such as the leopard.

Accordingly, the extended sampling periods used in this study are best interpreted as a pragmatic balance between two competing sources of error. Very short surveys reduce the risk of closure violation but can produce imprecise estimates because too few individuals and spatial recaptures are obtained; longer surveys improve precision by increasing detections and recaptures but progressively increase the potential for closure-related bias. For a relatively long-lived species such as the leopard, the available evidence indicates that the gains in precision from extending sampling can outweigh the relatively modest consequences of demographic closure violation over periods of several months, provided that surveys do not encompass major recruitment or population-turnover events. This approach is consistent with the central conclusion of Dupont et al. (2019): sampling duration should not be determined by an arbitrary requirement for a very short closure period, but by balancing precision, potential bias, species life history, and the timing of demographic events.

APPENDIX D. DENSITY, ABUNDANCE AND SPATIAL PATTERN IN BOTSWANA

Leopard densities varied considerably by sex, land use and geographic location (Figure 5; Table 2, see main text). Model selection provided unequivocal support for a single top-ranked SECR model (Table 3). In this model, leopard density (D) varied among survey sites (session) and between sexes (g); baseline detection probability (g_0) varied between two latent mixture classes ($h2$); and the spatial scale parameter (σ), which reflects the spatial extent of individual movements relative to camera stations, varied by both latent mixture class and sex. Mixture probabilities ($pmix$) were also estimated for the two latent classes. This model ($D \sim session + g, g_0 \sim h2, \sigma \sim h2 + g, pmix \sim h2$) had the lowest AICc (13,343.06) and an AIC weight of 1.00. The next-best model had substantially less support ($\Delta AICc = 74.57$; AIC weight ≈ 0), indicating essentially no model-selection uncertainty among the candidate models. The top-ranked model was therefore retained for estimating site- and sex-specific leopard densities and associated detection and movement parameters.

For each leopard density estimate, we calculated the standard error (SE), 95% confidence interval (CI), and coefficient of variation (CV) to quantify the uncertainty and precision of the estimates. Standard errors and 95% CIs were used to characterize the statistical uncertainty surrounding each density estimate, with CIs providing the range of plausible values for the underlying leopard density. The coefficient of variation, calculated as SE_i/D_i where i represents each sampled site, was used as a standardized measure of relative precision, allowing comparison of the uncertainty among density estimates from different survey sites. These metrics were used to assess the reliability and precision of the estimated leopard densities and to inform interpretation of differences among survey areas.

Site NG28 (Moremi) had the highest density with 2.74 leopards/100 km². Lowest density was observed in CT27 with 0.15 leopards/100 km². There was a single detection of one male leopard in site SO5 with no density estimation possible. We removed this site from the candidate set of sites used for density estimation; however, this site was used in occupancy modeling. For subsequent leopard density modeling, we retained rainfall and NDVI at the 20-km scale, landscape diversity at the 5-km scale, and latitude. Latitude was included as a spatial coordinate rather than as a scale-selected environmental covariate. These four predictors were used to construct the candidate leopard density models. The best-supported spatial scale identified for each covariate was subsequently retained for construction of the candidate leopard density and occupancy models.

Baseline detection probability (g_0) was estimated at 0.235 for individuals in latent class 1 and 0.028 for individuals in latent class 2 ($\beta = -2.352$; SE = 0.126). The movement parameter (σ) also differed between the two latent classes and between sexes. For females, σ was estimated at 2.04 km in latent class 1 and 4.73 km in latent class 2; corresponding male estimates were 3.40 and 7.87 km, respectively. Thus, individuals in latent class 2 had larger σ values than those in latent class 1 ($\beta = 0.840$; SE = 0.053), and males had larger σ

values than females within both classes ($\beta = 0.510$; SE = 0.040 SE). Estimated male density was lower than estimated female density across sites ($\beta = -0.942$; SE = 0.109).

Our candidate set of GLMs consisted of 943 camera stations distributed across 19 study sites after excluding site SO5, which was omitted because reliable density estimates could not be obtained. Among the candidate set of GLMs, the global model received the strongest support (AICc = 2051.44; AICw = 0.999). Leopard density decreased with increasing rainfall at the 20-km scale ($\beta = -0.262$; SE = 0.050), whereas it increased with date-matched NDVI at the 20-km scale ($\beta = 0.178$; SE = 0.054), landscape diversity measured using SHDI at the 5-km scale ($\beta = 0.293$; SE = 0.047), and nothing ($\beta = 0.424$; SE = 0.054).

The top-ranked GLM was used to generate a 1-km² predictive leopard density surface across Botswana (Figure 6). After restricting predictions to terrestrial habitat within the national boundary, predicted densities ranged from 0.002 to 0.075 leopards/km², with an overall mean of approximately 0.011 leopards/km². The final land-only surface covered approximately 579,075 km² and yielded a median national abundance estimate of 6,262 leopards (95% CI: 5,676–6,849) in Botswana.

Table 3. Model selection results for candidate spatially explicit capture–recapture (SECR) models used to estimate leopard density across survey sites in Botswana. Models were ranked using Akaike’s Information Criterion corrected for small sample size (AICc).

model	npar	logLik	AIC	AICc	Δ AICc	AICwt
D~session + g g0~h2 sigma~h2 + g pmix~h2	26	-6643.72	13339.44	13343.06	0	1
D~session g0~h2 sigma~h2 + g pmix~h2	25	-6682	13414.01	13417.35	74.574	0
D~session g0~h2 + g sigma~h2 + g pmix~h2	26	-6681.27	13414.53	13418.15	75.096	0
D~session g0~h2 sigma~h2 pmix~h2	24	-6754.85	13557.7	13560.78	218.263	0
D~session g0~1 sigma~h2 pmix~h2	23	-6760.97	13567.93	13570.76	228.495	0
D~session g0~h2 sigma~1 pmix~h2	23	-6777.19	13600.37	13603.2	260.935	0
D~session g0~b + g sigma~g	24	-6875.37	13798.74	13801.82	459.305	0
D~session g0~g sigma~g	23	-6879.78	13805.57	13808.39	466.132	0
D~session g0~1 sigma~g	22	-6880.89	13805.79	13808.37	466.35	0
D~session g0~g sigma~1	22	-6915.05	13874.09	13876.67	534.656	0
D~session g0~b sigma~b	23	-6939.12	13924.25	13927.07	584.813	0
D~session g0~b sigma~1	22	-6958.27	13960.55	13963.13	621.112	0
D~session g0~NDVI500_z sigma~1	22	-6958.56	13961.11	13963.69	621.676	0
D~session g0~1 sigma~1	21	-6963.56	13969.11	13971.46	629.674	0
D~session g0~1 sigma~b	22	-6963.21	13970.41	13972.99	630.976	0
D~1 g0~1 sigma~1	3	-7055.72	14117.44	14117.49	777.999	0

npar = number of estimated parameters

logLik = model log-likelihood

AIC = Akaike’s Information Criterion

AICc = AIC corrected for small sample size

Δ AICc = difference in AICc between each model and the top-ranked model

AICwt = Akaike model weight

INTERPRETATION OF PRECISION OF SECR DENSITY ESTIMATES

The precision of leopard density estimates was evaluated primarily using the coefficient of variation (CV), calculated as the standard error of the estimated density divided by the density estimate. The CV expresses uncertainty relative to the magnitude of the estimate, with lower values indicating greater precision. There is no universal statistical threshold at which an estimate becomes sufficiently precise for management purposes; acceptable precision depends on the species, population density, sampling conditions, management objectives, and consequences of the decision being considered. Nevertheless, CV values of approximately 20–30% have commonly been used as practical benchmarks in wildlife population studies. In a spatial capture–recapture assessment of boreal caribou, McFarlane et al. (2020) used CV as the principal measure of precision and considered estimates with CV <20% and relative bias <15% to represent favorable outcomes, while noting that estimates with CV <30% and absolute relative bias <20% may also be considered favorable, particularly for rare and low-density species for which very high precision can be difficult to achieve. Similarly, Kaschube et al. (2022) characterized capture–recapture estimates with CV <20% as relatively precise and those with CV values of 20–30% as marginally precise, while emphasizing that required precision depends on species characteristics and study objectives. These thresholds should therefore be regarded as guidelines rather than absolute criteria. For the present leopard survey, estimates with CV <30% were considered to have a generally useful level of precision for describing population status and broad spatial patterns, while estimates exceeding this threshold were interpreted with progressively greater caution. Importantly, CV measures precision rather than accuracy: a low CV indicates relatively little sampling uncertainty around an estimate but does not demonstrate that the estimate is unbiased. Consequently, the reliability and management relevance of each density estimate should be assessed using the CV together with its 95% confidence interval, potential sources of bias, adequacy of detections and spatial recaptures, model fit and convergence, survey design, and ecological plausibility. This broader interpretation is consistent with the spatial capture–recapture literature, in which estimator performance is evaluated using multiple attributes rather than precision alone (Efford, 2009; McFarlane et al., 2020).

APPENDIX E. OCCUPANCY MODELING RESULTS

A total of 381 of 947 camera stations recorded at least one independent leopard detection, yielding a naïve occupancy estimate of 0.40. Detection probability decreased during weeks with greater precipitation ($\beta = -0.255 \pm 0.059$ SE), lower minimum temperatures ($\beta = -0.173 \pm 0.079$ SE), and higher maximum temperatures ($\beta = -0.148 \pm 0.064$ SE), but increased with weekly NDVI ($\beta = 0.195 \pm 0.060$ SE). Occupancy probability decreased with increasing rainfall ($\beta = -0.431 \pm 0.082$ SE), while increasing with landscape diversity (SHDI; $\beta = 0.150 \pm 0.076$ SE) and northing (Y; $\beta = 0.196 \pm 0.090$ SE). We found that NDVI exhibited a weak positive relationship with occupancy ($\beta = 0.075 \pm 0.086$ SE, $P = 0.385$). The top-ranked occupancy model included rainfall, 5-km SHDI, and northing and received an Akaike weight of 0.41. The top model received the greatest empirical support ($AIC = 6047.24$), however, we did find some model selection uncertainty amongst 2 other models. Five candidate models collectively accounted for approximately 92% of the total candidate set weight and were retained for model averaged prediction. The model averaged predictions (Figure 7) exhibited modest predictive performance ($AUC = 0.63$, 95% CI = 0.59–0.67), indicating moderate predictability between predicted occupancy probabilities and observed station-level leopard detections. Model-averaged occupancy probability across Botswana’s land area had a mean of 0.41 and ranged from approximately 0.10 to 0.73.

APPENDIX F. GLOSSARY

Sampling Effort: Sampling effort describes how much work is put into trying to detect leopards with trail cameras. In simple terms, it combines how many cameras are used and how long they are left running in the field. For example, using more cameras or leaving them out for a longer time increases the chances of photographing leopards. Higher sampling effort generally leads to more reliable results because it gives leopards more opportunities to be detected.

Trap Nights: Trap nights are a simple way to measure sampling effort. One trap night equals one camera operating for one full day (24 hours). So, if 10 cameras are active for 10 days, that equals 100 trap nights. This measure helps researchers compare different studies and understand how much data was collected. If cameras stop working or are removed early, those lost days are not counted.

Leopard Detection: A leopard detection is any photo or video of a leopard captured by a trail camera. To avoid counting the same animal repeatedly in a short period, researchers often define “independent detections,” meaning that photos taken very close together in time may be counted as a single event. When image quality allows, individual leopards can be identified by their unique spot patterns, much like a fingerprint, which is especially important for estimating population size.

Probability of Detection: Probability of detection refers to the chance that a leopard will actually be photographed by a camera if it is present in the area. Even if a leopard lives nearby, it might not pass in front of a camera, or it might pass without triggering it. This means not all animals are detected. Researchers use statistical methods to account for this uncertainty, so they don’t underestimate how many leopards are truly in the area.

95% Confidence Interval: A 95% confidence interval is a way of expressing how certain (or uncertain) an estimate is. For example, if researchers estimate there are 10 leopards in an area, the 95% confidence interval might be 8 to 12. This means that, based on the data collected, the true number of leopards is very likely to fall somewhere within that range. A narrow range suggests a more precise estimate, while a wider range indicates more uncertainty, often due to fewer detections or lower sampling effort.

APPENDIX G. Q&A ABOUT LEOPARDS AND THE SCIF LEOPARD SURVEY

DO LEOPARDS MIGRATE?

Using “migration” for leopards is scientifically inaccurate. A more precise description would be: “leopards exhibit territorial home range behavior with dispersal-driven movement, rather than true migration.”

The African leopard does not exhibit migratory behavior as defined within the movement ecology framework. Migration is typically characterized as a temporally periodic, directional, and population-level displacement between spatially discrete ranges, generally associated with predictable seasonal variation in resource availability or reproductive requirements (Movement Ecology Paradigm; Animal Migration Definition). Such movements are typically synchronized across individuals and involve cyclical, often long-distance, relocations.

In contrast, *Panthera pardus* exhibits a predominantly resident spatial strategy structured around stable, individual-based home ranges with varying degrees of territorial exclusivity (Hunter et al. 2019; Loveridge et al. 2009). Space use is shaped by prey distribution, habitat configuration, conspecific density, and anthropogenic pressures, resulting in movement patterns that are continuous, plastic, and context-dependent rather than periodic or synchronized at the population level (Snider et al. 2021; Stein et al. 2011; Steyn and Funston 2009).

Long-distance movements do occur in the form of natal dispersal, primarily among subadult individuals, facilitating gene flow and territory establishment (Loveridge et al. 2010; Funston et al. 2013). However, dispersal is inherently stochastic, non-cyclical, and not linked to predictable seasonal drivers at the population level. In certain ecological contexts—particularly in low-density systems or landscapes with fluctuating prey availability (individuals may exhibit transient or quasi-nomadic movement patterns, though these remain facultative responses rather than obligate migratory strategies (Lindsey et al. 2011).

Accordingly, the use of the term “migration” in relation to leopard spatial ecology is not supported within a rigorous ecological framework. A more accurate characterization situates the species within a continuum of resident carnivore spatial dynamics, emphasizing home range fidelity, territorial structuring, and dispersal-mediated connectivity (Movement Ecology Paradigm).

DOES SECR MODELING ASSUME THAT DETECTORS ARE RANDOMLY PLACED IN THE SAMPLING AREA?

No—SECR (*secr* R package) modeling does not require detectors (e.g., camera traps) to be randomly placed.

Spatial capture–recapture (SECR) modeling does not require detectors to be randomly arranged, as the framework is fundamentally model-based rather than design-based. SECR explicitly models detection

probability as a function of the distance between an individual's activity center and detector locations, thereby accounting for spatial heterogeneity in detection without reliance on random sampling for unbiased inference (Efford & Fewster, 2013; Royle et al., 2014). Consequently, non-random detector placement is not only acceptable but is commonly used in practice, particularly in camera trap studies where arrays are often positioned along roads, trails, or other landscape features that maximize detection of target species (O'Connell et al., 2011; Burton et al., 2015). Simulation and empirical studies further demonstrate that SECR estimators are robust to a variety of detector configurations, provided that spatial design elements such as trap spacing and array extent are appropriate relative to the scale of animal movement (σ) (Sun et al., 2014). In general, detectors should be spaced such that they facilitate spatial recaptures (often on the order of $\leq 2\sigma$) and cover a sufficiently large area to sample multiple activity centers, as these factors have a stronger influence on estimator performance than randomness in placement (Efford, 2019; Sun et al., 2014). Therefore, in SECR-based leopard density surveys, including those using camera traps for large carnivores, the critical requirement is not random spatial arrangement but rather a well-designed sampling grid that ensures adequate spatial coverage and detection structure for reliable estimation of density.

Non-random detector placement is standard practice. In fact, many capture–recapture and camera trap studies deliberately use non-random placement to maximize detections: camera trap surveys are often “designed to maximize detections of the target species and [are] essentially non-random”. This includes placing detectors along trails, roads, or habitat features used by focal species. This is particularly relevant for large carnivores (e.g., leopards), where targeting movement corridors increases encounter rates and improves data quality.

CAMERA SPATIAL CONFIGURATION AND SPACING

Simulation studies show that SECR models can still produce accurate estimates under different configurations, as long as spacing and extent are appropriate (Sun et al., 2014). While SECR tolerates different designs, trap configuration strongly affects estimator performance. Key requirements include:

- Appropriate spacing relative to movement (σ)
- Trap spacing must reflect the species' movement scale
- Poor spacing (e.g., too wide) reduces spatial recaptures and biases parameter estimates
- Simulations show traps should generally be spaced $\leq \sim 2\sigma$ to ensure adequate detection
- Sufficient spatial recaptures
- Multiple detections of the same individual at different detectors are critical
- Sparse or poorly arranged detectors reduce the ability to estimate σ and density
- Adequate spatial extent
- Arrays must cover multiple home ranges to sample variation in activity centers

- Larger extents improve the number of individuals detected and parameter stability
- Flexibility in sampling design

A key strength of SECR is that it can accommodate varied detector layouts, including:

- Regular grids
- Clustered designs
- Adaptive or targeted placements



Leopards capture on camera in the Central Kalahari Game Reserve during the SCIF leopard survey, May 2023.



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