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Boots on the ground and ears in the canopy: evaluating the effectiveness of a combined monitoring approach in counter poaching in protected areas

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Introduction

Biodiversity is fundamental to human survival and economic development but faces significant threats from both natural processes and human activities (Prakash and Verma 2022). Anthropogenic activities have greatly increased over time, exacerbating negative impacts on biodiversity (Kumar and Verma 2017, Goudie 2018). Major drivers of wildlife population decline include habitat destruction, overexploitation, climate change and invasive species (Dirzo et al. 2014, Prakash and Verma 2022). These threats accelerate biodiversity loss and species extinction (Dirzo et al. 2014, Crooks et al. 2017, Newbold et al. 2020). Contributing mechanisms include land-use change; overharvesting; alterations on phenology, species interactions and distributions, enhancing spread of diseases and invasive species (Dueñas et al. 2021, Caro et al. 2022, Prakash and Verma 2022). As human activities expand, human-wildlife interactions increase, often resulting in lethal outcomes for wildlife (Decker and Dimensions 2009, Jochum et al. 2014).

In response, protected area management has become crucial and is considered one of the most important *in situ* conservation strategies (Chape et al. 2005, Dudley 2008, Acreman et al. 2020). Studies yielded varied results on their effectiveness (Stoll-Kleemann 2010, Geldmann et al. 2013, Acreman et al. 2020) due to the lack of universal metrics (Chape et al. 2005, Stoll-Kleemann 2010). Nonetheless, protected areas contribute to conserving unique ecosystems, (Rodrigues et al. 2004, Le Saout et al. 2013, Maxwell et al. 2020), reducing forest loss (Geldmann et al. 2013, Le Saout et al. 2013, Maxwell et al. 2020); and supporting wildlife populations persistence (Geldmann et al. 2013, Le Saout et al. 2013). They also provide ecosystem services such as water, food security and carbon sequestration (Scharlemann et al. 2010, Watson et al. 2014, Soares-Filho et al. 2023). In some developing countries, proximity to protected areas is related to higher household wealth and lower poverty rates (Griscom et al. 2017, Naidoo et al. 2019, Maxwell et al. 2020).

Despite their importance, protected areas often face illegal activities like poaching and deforestation (Bruner et al. 2001, Chape et al. 2005, Gonedelé-Bi et al. 2019), causing habitat loss (Carey et al. 2000), population isolation (Zeller et al. 2013, Beca et al. 2017), and even extirpation (Romero-Muñoz et al. 2019). Patrols, are a cost-effective and essential active protection strategy (Critchlow et al. 2017, Gonedelé-Bi et al. 2019). These ranger-led hikes help detect and reduce illegal activities, contributing to wildlife protection (Jenks et al. 2012, Linkie et al. 2015, Kablan et al. 2019, Astaras et al. 2020). However, patrols must be regularly evaluated to understand their spatial and temporal effects (Linkie et al. 2015, Astaras et al. 2017, Kablan et al. 2019). Such assessments are unfortunately rare due to biases in patrol coverage, limited personnel, and researchers' lack of control over collected data (Tscharntke et al. 2012, Linkie et al. 2015, Dobson et al. 2020, Moreto and Charlton 2021).

Measuring patrols effectiveness is crucial to informed, adaptive conservation (Balmford 2012). Tools like the Spatial Monitoring and Reporting Tool (SMART; https://smartconservationtools.org/) facilitate standardizing patrol data collection and analysis (Spatial Monitoring and Reporting Tool (SMART) 2022). SMART improves enforcement, management practices, ranger motivation, real-time monitoring and results communication (Hernandez-Aguilar et al. 2018, Kuiper et al. 2021).

Another novel valuable tool is passive acoustic monitoring (PAM), which uses recording devices to detect diverse sounds, such as animal vocalizations, chainsaws or gunshots (Thompson et al. 2010; Astaras et al. 2017). PAM is used to estimate species distribution and abundance (Hill et al. 2018; Burivalova et al. 2019; Stephenson 2020), characterize soundscapes (Hill et al. 2018, Sethi et al. 2020), asses impacts of human activities such as gas wells (Deichmann et al. 2017), construction (Santoso et al. 2021) and poaching (Martin et al. 2021). It can be applied across spatial and temporal scales (Krause and Farina 2016, Deichmann et al. 2017, Moreira Sugai et al. 2019) and is increasingly used for its efficiency and support for adaptive management (Astaras et al. 2017, Gibb et al. 2019). Adaptive management, an approach used in conservation, involves integrating design, management, and monitoring to test assumptions and facilitate ongoing adaptation and learning (Allen and Garmestani 2015).

Combining approaches may best support urgent conservation actions (Kamminga et al. 2018). Promising results have been shown by combining PAM with methods such as camera traps (Buxton et al. 2018b), casual or monitoring observations (Wrege et al. 2012, Zeppelzauer and Stoeger 2015) and occupancy models (Vu and Tran 2020). Due to the high cost of some technology devices used to study wildlife and threats, their use remains restricted to small or well-funded programs (Smith et al. 2021). Therefore, combined approaches may be particularly beneficial in Central American countries, where monitoring and research investment is limited (Rydén et al. 2020, Morales-Marroquín et al. 2022).

While SMART has improved the management of protected areas and reduced threats to wildlife mainly in Asia and Africa (Lynam et al. 2015, Astaras et al. 2020, Gabriel and Ravindran 2021, Kavhu and Mpakairi 2021), its use in the Americas remains limited. One notable case is its implementation in Belize's terrestrial protected areas to monitor illegal activities, enhance enforcement efforts, and support management decision-making through data collection and analysis (Hernandez-Aguilar et al. 2018). PAM, on the other hand, has been used to monitor poaching activity in Honduras and Guatemala (Escobar-Anleu 2019, Martin et al. 2021) and to evaluate the impact of extractive activities and guide mitigation strategies in Peru (Deichmann et al. 2017), Belize (Hill et al. 2018, Dobbins et al. 2020), Guatemala (Escobar-Anleu 2019) and Honduras (Martin et al. 2021). Despite the separate use of both methods in Central America, there are no studies assessing their combined effects or potential to enhance protected area management. Here we report results from a monitoring approach combining SMART patrols and PAM data to inform adaptive management in a protected area of Guatemala. Our findings represent the first published study of its kind for the Americas. We used information from SMART patrols and PAM in Sierra Caral Water and Forest Reserve, Izabal, Guatemala from 2017 to 2021 to answer two research questions: 1) does the combined monitoring approach and the derived adaptive management response yield a decrease in poaching activity? and 2) which covariates impact the number of detected poaching events?

Methods

Study area

We conducted this study within the Sierra Caral Water and Forest Reserve (SCWFR) located in Izabal, eastern Guatemala, a department bordering the Caribbean Sea (González-Bernat and Clifton 2021) and connecting Guatemala with Honduras and Belize. Izabal is key for regional biodiversity and wild cat connectivity, forming part of the Mesoamerican Biological Corridor and the Jaguar Corridor Initiative (Rabinowitz and Zeller 2010, Graham 2011, Petracca et al. 2014, 2018). Despite its importance, Izabal has one of the highest deforestation rates nationwide (Iarna-URL 2012, Redo et al. 2012, Sesnie et al. 2017), second only to Peten with 38% of its tree cover loss from 2002 to 2023 corresponding to humid primary forest (Global Forest Watch 2024). Additional threats include mining, monocultures, cattle ranching and cross-border illegal activities (IUCN 2014, González-Bernat and Clifton 2021).

Poaching is also a major threat and given that the Caribbean slope encompasses almost the entire extent of jaguar (*Panthera onca*) occurrence in Central America, reducing these threat is critical (Calderón et al. 2022). In addition to jaguars and the other four wild cat species present in Guatemala (puma, *Puma concolor*; ocelot, *Leopardus pardalis*; jaguarundi, *Herpailurus yagouaroundi*; margay, *Leopardus wiedii*), other threatened and/or intensely targeted species include the Central American tapir (*Tapirus bairdii*) and lowland paca (*Cuniculus paca;* Escobar-Anleu 2019). Other species we have documented as frequent poaching targets in the region include nine-banded armadillo (*Dasypus novemcinctus*), tinamous (*Crypturellus soui* and *Tinamus major*), Great Curassow (*Crax rubra*), white-nosed coati (*Nasua narica*), white-tailed deer (*Odocoileus virginianus*), and red brocket deer (*Mazama temama*), primarily hunted using firearms. Poachers often establish camps and use “tapescos”—elevated platforms made of sticks—to wait for animals, and use fire to cook them on-site.

SCWFR is a 190 km^2 protected area in southeastern Izabal (15°23'49.3"N - 88°42'58"W), bordering with Honduras (Fig. 1). It has three core zones (La Firmeza, Negro Norte, and Peñitas), surrounded by a multi-use zone and buffer area (Fig. 1). Comanaged by Fundación para el Ecodesarrollo y la Conservación (FUNDAECO) and the Consejo Nacional de Áreas Protegidas (CONAP), it was designated a Category III protected area in 2012 due to its high amphibian endemism, water source protection and role in regional connectivity with other protected areas (i.e., Cusuco National Park and Copán in Honduras) (Nowakowski and Angulo 2015). Category III protected areas are under control to regulate different pressures and may be made up of public and/or private land; they are considered relatively large, generally covered by forests but also with sites appropriate for sustainable production (CONAP 2016). Unlike other management categories that focus primarily on conservation, research or recreation or recreation, the goal of this category is to maintain the productivity of the areas and their resources in perpetuity, contributing to development through sustainable management and use (CONAP 2016).

SCWFR features subtropical moist and wet forests with an altitude ranging from 100-1221 masl, average temperature of 26.5°C and a mean annual precipitation of 3461 mm (INSIVUMEH 2010, Pérez-Consuegra et al. 2018). It contains one of the most biodiverse forest remnants in Central America (International Conservation Fund of Canada 2023), and harbors endemic species such as the blue pitviper (*Bothriechis thalassinus;* International Conservation Fund of Canada 2023), scarab beetle (*Phalangonia monzoni;* Smith 2021) and the Copan brook frog (*Duellmanohyla soralia;* Nowakowski and Angulo 2015), as well as rare mammal species (naked-tailed armadillo, *Cabassous centralis;* Pellecer et al. 2019) or not previously reported for the country (brown four-eyed opossum, *Metachirus myosuros*; Trujillo and Escobar-Anleu 2023). The area also supports migratory and threatened birds such as painted bunting (*Passerina ciris*), Canada warbler (*Cardellina canadensis*), Olive-throated parakeet (*Eupsittula nana*), highland guan (*Penelopina nigra);* slaty-brested tinamou, *(Crypturellus boucardi*) (Blandón et al. 2018, International Conservation Fund of Canada 2023, IUCN 2023).

We chose La Firmeza core zone (14.79 km^2) for this pilot study due to its accessibility, existing SMART patrols, and strong relationships with nearby local communities, which played an important role in monitoring activities. PAM and SMART patrols were implemented beginning in 2017. To evaluate if its combined use and the adaptive management response effectively contributed to counter poaching activity, we divided data collection into two phases: the pre-adaptive phase (September 2017-September 2018) and the adaptive phase (October 2018 onward), during which FUNDAECO implemented actions based on the initial findings.

Passive acoustic monitoring

From 2017 to 2021, we deployed Swift passive acoustic recording units (Ithaca, New York, United States) in the forest canopy of La Firmeza (Fig. 1). Swift units are autonomous recorders used to collect passive acoustic data for conservation and research purposes (Cornell University 2021b). We used them to detect gunshots as a proxy for poaching activity (Hill et al. 2018, Astaras et al. 2020).

To estimate detection distance, we deployed six devices and produced nine shotgun shots at various altitudes and distances. We estimated a radius of detection of 500 m. To ensure the independence of events, we deployed six recorders > 1 km apart. Swift units were placed at the same locations during seven periods from 2017-2021 (November 2017-January 2018; June-September 2018; December 2018-April 2019; December 2019-March 2020; March-June 2020; May-August 2021; and September-November 2021). We discarded data from December 24th - January 2nd, as those included major holidays when fireworks are frequently used, making it difficult to distinguish from gunshots. At the beginning of each period, we ensured the Swift units were properly functioning and set them to continuously record (24 hours/day). At the end of each period, we removed them and used a gunshot detection algorithm (Wrege et al. 2017) followed by confirmation using RAVEN PRO (Cornell University 2021a). RAVEN PRO enables acquisition, visualization and analysis of acoustic data (Cornell University 2021a). Each episode of gunfire, whether isolated or in busts, was considered a poaching event.

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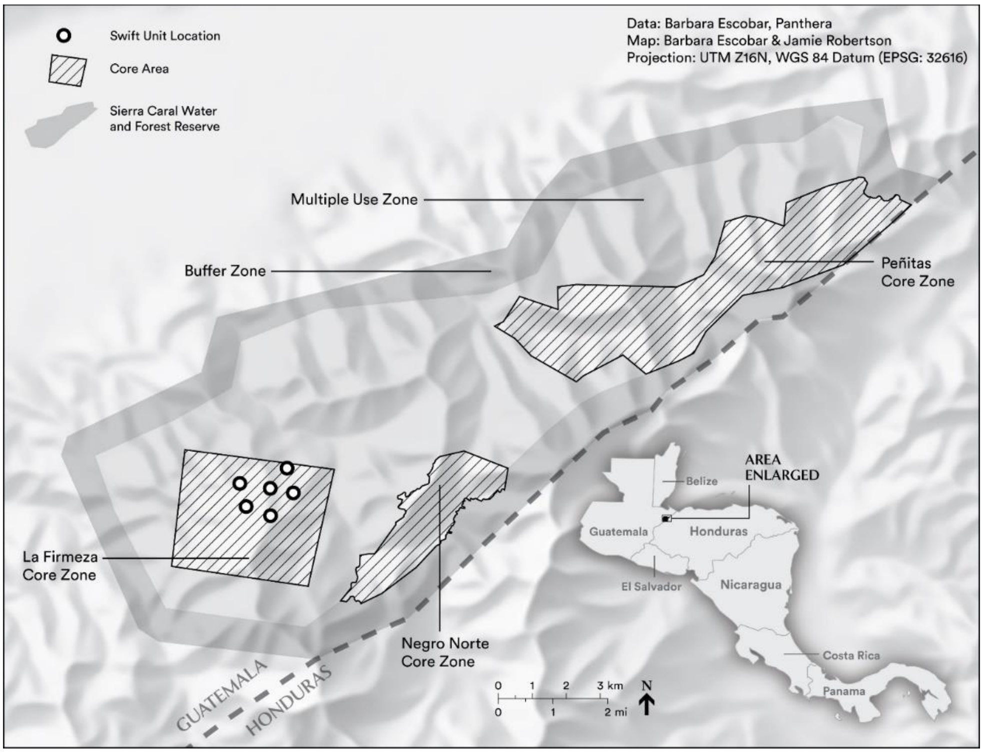
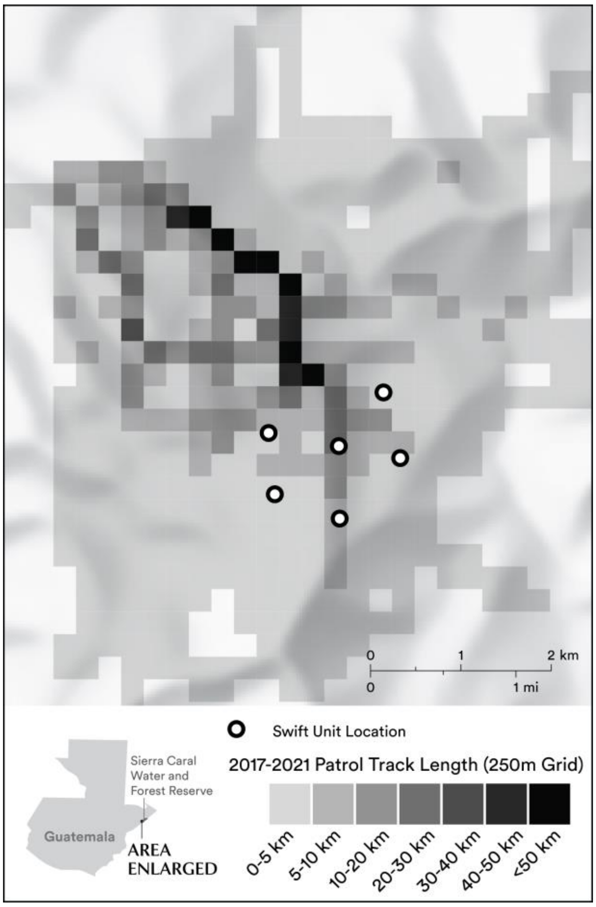
Figure 1. Location map of Sierra Caral Water and Forest Reserve (SCWFR) in Guatemala depicting its zonation and the location of the Swift units (n=6) in the core zone “La Firmeza”.



SMART patrols

La Firmeza was patrolled by a team of local rangers using the SMART approach from 2017 to 2021, walking an average distance of 51.53 km per month (Fig. 2). Date, time, GPS coordinates, track and poaching evidence were recorded for each patrol. Poaching events included physical evidence such as bullet casings, camping and fire pit sites, temporary structures or wildlife remains. We entered data into a SMART database created for SCWFR. We calculated metrics on patrol effort (person-hour), distance traveled (km) and identified key poaching locations and dates.

Figure 2. SMART patrol intensity and locations of Swift units in La Firmeza core zone, Sierra Caral Water and Forest Reserve (SCWFR), Guatemala. This map shows the locations of Swift units (circles) and patrol intensity based on SMART patrols from 2017 to 2021, represented in a 250m grid where darker shades indicate higher patrol effort.



Data organization and management response

The period from September 2017 to September 2018 was defined as the baseline (pre-adaptive phase). The adaptive phase began in October 2018 with the implementation of actions as the management response, including increasing patrols on weekdays with higher poaching activity and focusing patrols in areas with higher evidence of poaching. These patrols were mainly conducted by local rangers, but this information also allowed the planning of inter-agency patrols, involving government entities capable of making arrests. Based on local knowledge of the area, we know that increased presence in the area and sporadic interagency patrols with the potential for arrests and captures contribute to deterring poaching activity. Our patrols goal was to deter poaching and dismantle camps and other poaching structures, such as “tapescos”.

To evaluate if the combined SMART-PAM protocol and the management response effectively contributed to reduce poaching, we aggregated gunshots and patrol data for all four years in a combined data framework to analyze poaching patterns (Astaras et al.

2020). We used a 2x2 km grid in the area to facilitate spatial aggregation of the combined data (SMART patrols and PAM events). This database was also used to explore covariate effects on poaching detection.

According to the findings from the combined SMART patrols and PAM protocol during the pre-adaptive phase, several management actions were implemented starting in October 2018 (adaptive phase). These actions included increasing patrols on weekdays with higher poaching activity and conducting more frequent patrols in areas with significant evidence of poaching.

Data analysis

We used the number of detected poaching events as the response variable and tested 11 explanatory variables (Table 1; Min-Venditti et al. 2017; Ferreguetti et al. 2018; Astaras et al. 2020) grouped into temporal, effort and environmental categories. Temporal covariates included management phase (pre-adaptive or adaptive) and year. Effort covariates included distance patrolled, patrol effort and number of Swift units per grid. Environmental covariates included Normalized Difference Vegetation Index (NDVI), precipitation, moon illumination (%), and distances to water, towns and roads (Table 1). We calculated Pearson correlation coefficients (r) to assess the relationships among covariates that could be related (e.g. distance patrolled and patrol effort) and retain only those relevant to avoid redundancy. We considered a strong correlation as $r > 0.5$ for positive and $r < -0.5$ for negative correlations. However, none showed strong correlations.

Table 1. Covariates and their expected influence used in the general linear models (GLMs) to predict poaching activity events detected with the combined protocol (SMART patrols and passive acoustic monitoring) in the La Firmeza core zone of the Sierra Caral Water and Forest Reserve (SCWFR), Guatemala (2017-2021).

Category	**Covariate**	**Unit**	**Range (min-max)**	**Mean value**	**Expected influence**
Temporal	Management phase	Pre-adaptive or adaptive	NA	NA	More poaching events during the pre-adaptive phase.
	Year	Year	2017-2021	NA	Poaching events will decrease over the years.
Effort	Distance patrolled	Km	1.18-48.86	9.63	More poaching events detected with longer patrolled distances.
	Patrol effort	Person-hour	6.75-168	54.46	More poaching events detected with higher patrol effort.
	Number of Swift recorders per grid	Number	1-3	NA	More poaching events in grids with higher number of Swift recorders.
Environmental	Normalized Difference Vegetation Index	-	0.72-0.88	0.84	More poaching events in locations with higher NDVI.
	Precipitation	Mm	0-110	3.56	Less poaching events with higher precipitation.

	Moon illumination	%	NA	NA	Less poaching events with higher moon illumination.
	Distance to water	Km	0.05-1.81	0.25	More poaching events near water.
	Distance to towns	Km	1.92-4.83	3.34	More poaching events near towns.
	Distance to roads	km	3.29-6.38	5.69	More poaching events near roads.

Distance patrolled and patrol effort were estimated using SMART's patrol query option. The number of recorders refers to the number of Swift units per 2x2 km grid. Precipitation data used was from the closest meteorological station (Livingston, Izabal) and requested from the Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH) for the entire study period. We used precipitation data specific to the days and nights when poaching events were detected. The percentage of moon illumination was obtained using MOONPHASE SH software (version 3.3; Henrik Tingstrom) for every night when gunshots were detected. Distances (to water, towns and roads) were calculated using QGIS Spatial Analyst tool (QGIS 2024). NDVI quarterly stacks for each year of the study were built from Landsat images (Gorelick et al. 2017) using Google Earth Engine Data Catalog.

We evaluated the effectiveness of the combined SMART-PAM protocol and the adaptive management response using general linear models (GLMs) within the *stats* package (Bates et al. 2015) in *R* software (R Core Team 2013). With this we also determined how the temporal, effort and environmental covariates affected the number of detected poaching events. In all cases, we tested for normality of the residuals and used Corrected Akaike Information Criterion (AICc; recommended for small sample sizes for model selection (Anderson and Burnham 2002, Bonakdari and Zeynoddin 2022). Using a systematic approach, guided by the Akaike Information Criterion (AIC) and the p-values, we sequentially eliminated covariates with least statistical significance or minimal effect on model explanatory power. This iterative process resulted in 11 models, each progressively refined by removing one covariate at a time. We retained the top model and those that were within 2 AICc units of the top model (Anderson and Burnham 2002), basing our final selection on models that balanced simplicity and explanatory ability, procuring to retain covariates that significantly contributed to understanding the data.

We considered temporal covariates such as year and management phase since we expected to see a reduction in the number of detected poaching events over time. We also considered covariates such as distance patrolled (km), patrol effort (person-hour) and number of recorders, since they can affect the detection of poaching. In other words, we expected that larger groups of rangers, larger distances of patrolling and more recorders (per 2x2 km grid) would result in a higher detection of poaching events. Precipitation (Rashidi et al. 2016), percentage of moon illumination (Pratas-Santiago et al. 2017, Astaras et al. 2020), NDVI (Rashidi et al. 2016), distance to water, distance to towns and distance to roads (Dobson et al. 2020) are also covariates that can affect poaching activity since they can influence poachers' visibility and mobility, site access and the probability of encountering wild species.

During the preparation of this work we used ChatGPT in order to help reduce the word count and review the phrasing of some ideas. After using this tool, we reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Use of Artificial Intelligence

During the preparation of this manuscript, we used ChatGPT (OpenAI, 2024) to assist with reducing the word count and review the phrasing of certain sentences. We carefully reviewed and edited all text resulting from its use.

Results

From September 2017 to December 2021, 273 SMART patrols were conducted within the core area of La Firmeza in SCWFR. These patrols covered 2,628 km and represented a 14 868 person-hours effort. This effort yielded evidence of 313 poaching events. The location of the Swift units remained the same throughout the study. In total, Swift units sampled for 2491 days covered 18.84 km^2 (on average) during each PAM sampling period. All together, 506 poaching events (gunshots) were detected by PAM. We estimated a 67.52% overlap between the Swift units detection buffer and the patrolled areas.

Eleven candidate models were generated, each incorporating the management phase along with other frequently included covariates such as kilometers patrolled, percentage of moon illumination, patrol effort, and distance patrolled. From these, four competing models were selected according to deltaAICc and AICc weight (Table 2). The most parsimonious model included only management phase (mod11; Δ AICc = 1.15, AICw = 0.19). However, the top model also included distance patrolled (mod10; Δ AICc = 0.00, AICw = 0.34). The other top models also included percentage of moon illumination (mod9, Δ AICc = 0.75, AICw = 0.23) and patrol effort (mod8; Δ AICc = 1.71, AICw = 0.14).

Our results indicate that management phase had a significant effect on the number of detected poaching events (Table 3). The monthly average of poaching events during the pre-adaptive phase was reduced from 21 in the adaptive phase to 14 after using the SMART patrols and PAM information to adapt the patrol locations (Fig. 3). Other covariates that affected the number of detected poaching events were a longer distance patrolled, and higher percentage of moon illumination, which resulted in a higher number of detected poaching events, while an increase in patrol effort resulted in a lower number of poaching events detected with the combined protocol.

Table 2. Summary of candidate model set of 11 general linear models (GLMs) predicting poaching activity events detected with the combined protocol (SMART

patrols and passive acoustic monitoring) in the La Firmeza core zone of the Sierra Caral Water and Forest Reserve (SCWFR), Guatemala (2017-2021). We report AICc, delta AICc (ΔAICc) and AICc weight for each candidate model.

Model	**Covariates***	**AICc**	**Δ AICc**	**AICc weight**
Selected models				
Model 10	Manp + km	231.71	0.00	0.34
Model 9	Manp + km + moon	232.46	0.75	0.23
Model 11	Manp	232.86	1.15	0.19
Model 8	Manp + km +Peff + moon	233.42	1.71	0.14
Other models				
Model 7	Manp + km + Peff + moon + Dt	235.10	3.40	0.06
Model 6	Manp + km + Peff + ppt + moon + Dt	237.04	5.34	0.02
Model 5	Manp + km + Peff + ppt + moon + Dt + Dr	239.13	7.42	0.01
Model 4	Manp + Rec + km + Peff + ppt + moon + Dt + Dr	241.57	9.87	0.00
Model 3	Manp + Rec + km + Peff + ppt + moon + Dw + Dt + Dr	244.10	12.40	0.00
Model 2	Manp + Rec + Year + km + Peff + ppt + moon + Dw + Dt + Dr	246.75	15.05	0.00
Model 1	Manp + Rec + Year + km + Peff + ppt + moon + Dw + Dt + Dr + NDVI	249.53	17.82	0.00

* Manp – management phase, km – distance patrolled, moon – moon illumination percentage, Peff – patrol effort, ppt – precipitation, Dt – distance to towns, Dr – distance to roads, Rec – number of recorders, Dw – distance to water, NDVI – Normalized Difference Vegetation Index

Figure 3. Poaching events detected by SMART patrols and Passive Acoustic Monitoring (PAM) across management phases

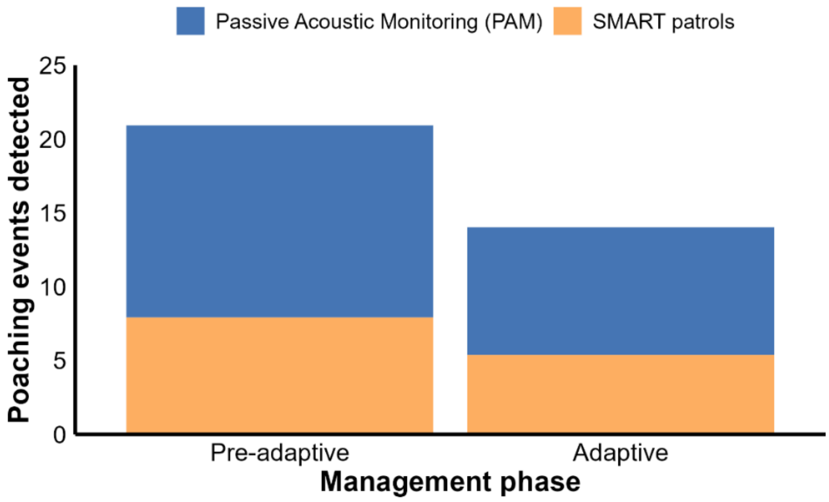


Table 3. Results of the top model selected by AICc, which includes fixed effects of management phase (Manp) and distance patrolled (km) as they relate to poaching activity detected with the combined protocol (SMART patrols and passive acoustic monitoring) in La Firmeza core zone of the Sierra Caral Water and Forest Reserve (SCWFR), Guatemala (2017-2021).

Effect	**Estimate**	**SE**	**z-value**	**p-value**
(Intercept)	0.0778	0.23	0.29	0.77
Manp	0.39	0.18	2.15	0.03**
km	0.04	0.02	1.89	0.06*

**significant at 0.05, *significant at 0.1

Discussion

Our study is the first in the Americas to evaluate the effectiveness of a combined protocol involving SMART and PAM patrols in protected areas, along with the management response derived from the monitoring data, in reducing poaching events. Previous studies evaluated the effectiveness of patrols in reducing poaching (Wiafe 2016, Moore et al. 2018, Kablan et al. 2019), while others used PAM to measure poaching activity (Browning et al. 2017, Martin et al. 2021, Martínez Pardo et al. 2022). The only similar study was conducted in Korup National Park, Cameroon, where PAM was used to explore hunting activity in the protected area. Anti-poaching patrols were adapted in response to the evidence gathered from PAM and the effectiveness of the new patrol strategy was evaluated (Astaras et al. 2020).

Combined approach and adaptive management to reduce poaching

Our results indicate that the number of poaching events detected were significantly higher during the pre-adaptive management phase than after the management response was implemented. This supports the interpretation of an overall reduction in poaching activity, likely due to the complementary nature of both methods, which were used to inform effective adaptive management practices.

Patrols are a widely employed tool within protected areas and are known for their cost-effectiveness, as they are often simultaneously used to prevent illegal activities as well as to collect information about ecosystems and their biodiversity (Kuiper et al. 2020, 2021). Cases worldwide have shown that patrols significantly contribute to reducing poaching in protected areas (Carter et al. 2017, Moore et al. 2018, Gonedelé-Bi et al. 2019), even outperforming other methods to deter illegal activities (Van Doormaal et al. 2022). Compared to other studies in similar areas and systems. our patrol metrics were. Korup National Park in Cameroon has an area of 1,259 km^2 and a monthly patrolled distance of 80 km (Astaras et al. 2020), and Cusuco National Park in Honduras has an area of 234.4 km^2 and a monthly patrolled distance of 101.8 km (Martin et al. 2021). In comparison, SCWFR has an area of 190 km^2 and our monthly average distance patrolled was 51.53 km. These differences are likely associated with the different size of the areas, the very challenging topography and the limited resources of management agencies in our study area, which can hinder covering large distances compared to other areas where more patrols and/or larger ranger teams are feasible.

No matter how much patrol effort is conducted, patrols also have inherent limitations, such as being typically conducted only during daylight hours and often with understaffed ranger teams responsible for monitoring vast areas (Astaras et al. 2020, Dobbins et al. 2020), which was the case in our study area. Although rangers are trained and experienced in conducting patrols and systematizing the collected information, biases in the data collected may exist due to multiple factors (Dobson et al. 2019, Van Doormaal et al. 2022). Landscape features such as vegetation type, topography, and accessibility of certain sites within the protected area can determine the extent to which certain areas are patrolled and illegal events detected (O'Kelly et al. 2018, Kuiper et al. 2020, Moore et al. 2021). Factors such as the level of experience, training, and motivation of the rangers, as well as equipment failures or human errors (such as forgetting to collect certain data), also influence the information gathered during patrols (Kavhu and Mpakairi 2021, Kuiper et al. 2021, Van Doormaal et al. 2022). All this may lead to lower detection of poaching activity and an underestimation of poaching events.

PAM has been used in varied environments and in countries such as Brazil (Martínez Pardo et al. 2022), Honduras (Martin et al. 2021), Cameroon (Astaras et al. 2020), Peru (Deichmann et al. 2017) and Belize (Katsis et al. 2022) to characterize poaching activity and propose management measures to reduce these threats within protected areas. This method has multiple advantages including that is a cost-effective tool that can quickly assess changes, it quantifies human activity in real time, and facilitates monitoring several locations over long time periods (Wall et al. 2014, Astaras et al. 2017, 2020, Buxton et al. 2018a). While PAM is often perceived as cost-effective, in many Global South contexts, technology-based solutions perpetuate a form of neoliberal conservation, in which countries become dependent on expensive and inaccessible technologies manufactured in the Global North, exacerbating structural inequalities in conservation (Arrighi et al. 2003, Berger-Tal and Lahoz-Monfort 2018).

Given that all monitoring methods have limitations, a combination of them can be a more effective approach to reduce illegal activities such as poaching (Gavin et al. 2010, Knapp et al. 2010). Since, in the context of poaching detection and reduction, PAM solely relies on gunshot sounds as evidence to detect poaching activity (Astaras et al.

2020, Martin et al. 2021, Hedley et al. 2022, Martínez Pardo et al. 2022), it overlooks other indicators that are only detectable through patrols, such as animal remains, campsites, fires, and other poachers' traces. While the detection of certain poaching evidence may be more effective with patrols (Van Doormaal et al. 2022), specifically identifying poachers is challenging with this method, as they actively seek ways to evade patrols (Burton et al. 2012). This coupled with the fact that when Swift units are in the field, they collect data 24 hours a day (unlike patrols), highlights the utility and importance of combining these complementary methods. We recommend these kind of combined approaches since each method allows us to observe spatio-temporal patterns that the other method may not necessarily detect, thereby promoting a more comprehensive understanding of poaching activity in the protected area.

Covariates effect on poaching events detected

Although we did not find that the combined protocol and its management response reduced poaching over the years of our study, we did observe a reduction in detected poaching events during the adaptive phase compared to the pre-adaptive phase. Other covariates that influenced the number of detected poaching events were distance patrolled and percentage of moon illumination. Both of these covariates were positively associated with an increase in the number of poaching events detected. The positive effect of distance patrolled has been documented in previous studies and could be attributed to a higher probability of finding more poaching incidents when walking greater distances, or perhaps due to poaching activities being concentrated in areas more distant from ranger meeting points (Linkie et al. 2015, Moore et al. 2018). Walking greater distances can also mean that park rangers were able to reach places that they do not frequent very often, so over time, more poaching evidence can accumulate. Furthermore, when walking greater distances, park rangers could reach some sites with habitat conditions preferred by poachers, such as vegetation that provides enough cover (Rashidi et al. 2016). Therefore, this result may be more reflective of increased detection of poaching events rather than an increase in the occurrence of poaching events. On the other hand, patrol effort was associated with a lower number of poaching events. Previous studies have found similar results where a higher patrol frequency and effort is associated with lower occurrence of poaching activity (Linkie et al. 2015). This could happen if rangers repeatedly patrol the same areas (Moore et al. 2021), leading to greater presence that deters poachers by sending the message that the area and its wildlife are being protected (Gonedelé-Bi et al. 2019, Moore et al. 2021). On the other hand, some studies have shown that detection of poaching activity evidence varies according to other factors such as area accessibility (Kuiper et al. 2021), the training and experience of the park rangers, as well as their motivation and the novelty of the patrol purpose (Lewandowski and Specht 2015, Kuiper et al. 2021). In our study area, while large groups of rangers (which may be associated with increased person-hour effort) could deter poachers, they may also be easier for poachers to detect and evade. Additionally, larger groups might hinder participants from staying focused and, consequently, finding less evidence (Van Doormaal et al. 2022).

Moon illumination has been considered in numerous studies, as it impacts the activity patterns of wildlife and plays a role in the behaviors of poachers (Pratas-Santiago et al. 2017, Rahman and Mardiastuti 2021, Geldenhuys 2023). In our study, we found number that more poaching events were associated with a higher percentage of moon illumination. While some previous studies have found the opposite, these have usually been carried out in open habitat or with less dense vegetation (e.g. deciduous mixed oak woods) than that found in tropical humid forests like the one we work in (Astaras et al. 2020, Gordigiani et al. 2022). Other studies suggest that higher rates of poaching activity during times of increased moon illumination are due to less experienced poachers using the increased lighting conditions (Koen et al. 2017) or due to the activity of some species of interest (Pratas-Santiago et al. 2017, Ghoddousi et al. 2022, Gordigiani et al. 2022). In our study area, poachers likely take advantage of the moon's brightness to enhance visibility and improve their performance (Ferreguetti et al. 2018, Guerisoli et al. 2023), particularly due to the dense vegetation in the area and because patrols are only carried out during the day.

In some previous studies, precipitation had a significant negative impact in poaching activity (Gobush et al. 2008, Nhleko et al. 2022), since intense rainfall can considerably change vegetation, overflow streams, impede poacher movement, reduce visibility, and hinder the use of weapons (Gobush et al. 2008, Astaras et al. 2017). However, in lowland tropical humid forests like SCWFR, precipitation changes during wet and dry seasons are typically less pronounced compared to other ecosystems (Clark and Clark 1992, Feeley and Silman 2011). As such, poachers are likely accustomed to the challenges that precipitation variations can pose, which may explain why precipitation had little influence in our study.

Despite having a significant effect on poaching activity in previous studies, NDVI and distances (to water, to towns and to roads, Rashidi et al. 2016; Moore et al. 2021; Ghoddousi et al. 2022) were not found to be significantly associated to poaching evidence in our system. We attribute this result to the narrow range of values in those covariates (Table 1), which makes it difficult to detect an effect. Therefore, we suggest considering these covariates in future studies, as the influence may be significant and vary in this and other regions with broader ranges of covariate values. It is also crucial to highlight that, although we have noticed a decline in poaching incidents within the study area, this could indicate a shift of poaching activities to regions where our monitoring resources are insufficient (Astaras et al. 2020, Van Doormaal et al. 2022).

Conclusions

Our findings suggest that employing complementary techniques, such as SMART patrols and PAM, not only provides valuable data across different spatial scales and timeframes but can also contribute to reduce poaching within protected areas. These techniques allow local managers to gain a comprehensive understanding of poaching activities, facilitating the implementation of adaptive management strategies to effectively reduce threats. We also provide a foundation for understanding how some explanatory variables of poaching activity, like distance patrolled, percentage of moon illumination and patrol effort can significantly affect the number of detected poaching events in areas with similar contexts. Other potentially influential covariates, such as distance to water, roads, towns, and NDVI, did not show significant impact in our case, but this may have been the result of the narrow range of values available in our study, and we recommend these covariates should be investigated in future studies.

There is an urgent need to increase protection and monitoring efforts to cover larger or less prioritized areas. We also advocate for expanding methods beyond relying solely on technology by integrating complementary techniques, especially when cost-related limitations hinder acquiring equipment from other countries, as is often the case in countries of the Global South. Although implementing PAM can be expensive—especially due to the initial investment in recorders and accessories, as well as the learning curve for installation and data analysis— we consider it has been an effective method in our study area. PAM has contributed substantially to detecting poaching activity and complemented the information gathered through patrols. Based on this experience, we strongly recommend the use of PAM and aspire to expand its coverage to cover larger areas. However, we recognize that such expansion requires financial and technical resources that are not always available. This highlights the importance of integrating complementary approaches rather than relying solely on externally sourced technologies. Combining methods like PAM with patrols can offer a robust, realistic and context-appropriate monitoring strategy in areas like the one of our study.

We recognize the importance of reinforcing patrols, since they serve multiple purposes: gathering evidence of poaching and other illegal activities (e.g. logging), as well as biodiversity monitoring. Additionally, promoting patrols that employ local people may benefit communities near protected areas by providing economic alternatives and greater community involvement. Given the unique challenges of managing a bordering protected area, such as SCWFR, we recommend promoting binational collaboration with Honduras and enhancing inter-institutional cooperation to support local managers in undertaking conservation actions in the area. We recognize that poaching in the area is a complex issue. Therefore, we also recommend that this inter-institutional collaboration, aim to uncover the underlying factors leading to poaching by investigating the motivations of poachers in the area, allowing a more efficient and comprehensive approach to addressing the threat.

In our case, acoustic data was used exclusively to generate synthesized and actionable outputs for local protected area managers to facilitate decision-making. However, we recognize the importance of ensuring a responsible use of digital technologies applied in conservation, ensuring that they remain aligned with transparent, locally relevant, and ethical practices. We encourage future implementations of PAM and similar technologies to be mindful of these risks and to be guided by principles of local engagement and accountability throughout the monitoring process.

Finally, as researchers from the Global South, we acknowledge the persistent structural North/South inequalities that shape access to resources for conservation technologies. Therefore, we recommend that future studies, particularly those conducted in the Global South, address these imbalances not only through technical solutions but also by considering broader contextual factors, limitations and opportunities. We also emphasize the importance of fostering deeper and long-term collaboration, co-production and investment in local capacities to ensure more sustainable and equitable conservation efforts.

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