Biological Conservation 253 (2021) 108909

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Policy analysis

Randomized hotspot strategy is effective in countering bushmeat poaching by snaring

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ARTICLE INFO

Keywords:
Bushmeat
Deterrence
Patrolling
Poaching
Protected areas
Snares

ABSTRACT

Bushmeat poaching using snares is a widespread problem in African and Asian protected areas. Snares are hard to detect, and desnaring is resource-intensive. Research into this form of poaching has thus far concentrated on the identification of spatial snaring patterns and association of these patterns with selected variables. However, no research to date has examined and compared desnaring strategies. We developed and tested a predictive map to assess the likelihood of snaring in a Kenyan World Heritage site, based on 147 km of desnaring transects. This map was the basis for the simulation of desnaring strategies that leveraged insights from both criminal pattern theory and exploitation/exploration tradeoff theory. The proportion of recovered snares (desnaring) is maximized by increased visits to areas that are adjacent to snare recovery sites. Moreover, a strategy that employs a randomized hotspot search identifies more snares that were replaced by poachers after initial desnaring. A desnaring strategy that balances visits to known poaching hotspots (exploitation) with efforts to identify other hotspots (exploration) is more effective than a sequential site-by-site approach. This strategy has the added advantage of introducing patrolling patterns that are less predictable for poachers.

1. Introduction

The consumption of meat from wild animals (bushmeat) contributes to an extinction threat for over 300 terrestrial mammals (Ripple et al., 2016), empty forests and savannas (Lindsey et al., 2012; Ripple et al., 2015), and transmission risk of zoonotic diseases such as Ebola, HIV, and corona-viruses (Jones et al., 2008; Lam et al., 2020; Wilkie, 2006). Research on bushmeat hunting has concentrated on forest biomes, but the threats to biodiversity are increasingly recognized for African savannas (van Velden et al., 2018), where bushmeat hunting and consumption have become commercialized and widespread (Lindsey et al., 2013; van Velden et al., 2018).

The illegal hunting of wildlife for the consumption and trade of wild meat (bushmeat poaching) is increasing in protected areas, as wildlife populations in unprotected areas continue to dwindle (Lindsey et al., 2013; Ripple et al., 2015). Managers of protected areas report unsustainable hunting as a major threat (Schulze et al., 2018). However, most of them have insufficient resources at their disposal to provide adequate protection for the biodiversity within the confines of the areas under their supervision (Coad et al., 2019). Patrolling protected areas is expensive and can consume up to 66% of the operational budget (Plumptre, 2019).

Snaring is the most frequently used method for bushmeat poaching (Lindsey et al., 2013). Snares are cheap to make and hard to detect (Gray et al., 2017; O'Kelly et al., 2018b). Snares frequently catch animals that were not targeted by poachers, such as large predators (Loveridge et al., 2020), elephants (*Lox-odonta africana*) (Becker et al., 2013), and tapirs (*Tapirus indicus*) (Campbell et al., 2019). Poachers have been observed to switch to snaring from other hunting methods when confronted with intensified patrolling (Gandiwa et al., 2013; Henson et al., 2016; Jachmann, 2008). Removal of snares (desnaring) is labor-intensive, expensive (Jachmann, 2008), and specialized work (Wato et al., 2006). Managers of protected areas and other practitioners have called for research into improved snare detection and deterrence of bushmeat poachers, in response to the increasing and widespread use of snares (Gray et al., 2018; Masolele, 2018).

We attempt herein to increase the effectiveness of desnaring strategies by leveraging three observations from environmental criminology. This group of theories seeks to understand the spatial and temporal patterns of crime within the physical and situational contexts in which

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https://doi.org/10.1016/j.biocon.2020.108909
Received 15 May 2020; Received in revised form 25 November 2020; Accepted 30 November 2020
Available online 16 December 2020

these crimes occur (Summers and Guerette, 2018).

First, criminal pattern theory (Brantingham et al., 2016; Brantingham and Brantingham, 1993) posits that potential offenders' daily spatial movements result in building up familiarity with the space around nodes of activity (e.g. work place, home) and the paths between them. Motivated offenders can thus become aware of criminal opportunities, which are not uniformly distributed in the environment. Successful crimes may be repeated and become part of a crime script (Summers and Guerette, 2018), which can result in an increased risk for additional crimes in the vicinity of previous crimes ("near repeats" or "contagion", Caplan and Kennedy (2016); Pease and Farrell (2017)). This theory predicts that poaching will occur along "edges", such as roads and park boundaries; that snares will not be uniformly distributed across the protected area, but will rather occur in hotspots; and that these hotspots will tend to be persistent.

Second, crime's clustering properties (Eck and Weisburd, 1995; Weisburd et al., 2014) have been confirmed for wildlife crime (Kurland et al., 2017). Snares inside protected areas are placed in clusters (Kimanzi et al., 2014; Risdianto et al., 2016), often occurring along the park's boundaries (Loveridge et al., 2020; Mudumba et al., 2020; O'Kelly et al., 2018b; Wato et al., 2006) and along roads bordering or dissecting them (Jenks et al., 2012; Mudumba et al., 2020; Wato et al., 2006; Watson et al., 2013). The stability of poaching hotspots was confirmed by Critchlow et al. (2015), who found that the best predictor for illegal activities in protected areas was their locations in previous years.

Third, the routine activity approach (Cohen and Felson, 1979) posits that crimes can occur where there is a confluence of willing offenders and suitable victims in the absence of capable guardians. On this basis, we expected snaring to occur in locations where poachers are not directly visible to rangers, and where animals forage or rest. This combination of circumstances is found in savanna environments where bushes transition to open areas. A relationship between snare abundance and land cover density was identified in the context of forests (O'Kelly et al., 2018b).

The uneven distribution of crime in time and space raises the important question of how the efforts of desnaring teams in protected areas should be allocated. The stability of hotspots and the possibility of contagion require repeat visits to identified snaring locations, and this increased localized effort must be balanced against the requirement to identify hotspots elsewhere within the protected area.

No study hitherto has examined and compared the effectiveness of different desnaring strategies. Here, we apply a method aimed at reducing the search area for desnaring within a Kenyan protected area, followed by a field test to confirm our results. We then simulate desnaring strategies that explicitly address the spatial and temporal clustering properties of crime. We find that balancing visits between known snaring hotspots (exploitation) and discovery of new snares (exploration) yields a higher snare discovery rate than would be expected based on snare detection probabilities. Moreover, this strategy is more effective in finding snares that were replaced by poachers after initial desnaring while reducing the predictability of desnaring patrols.

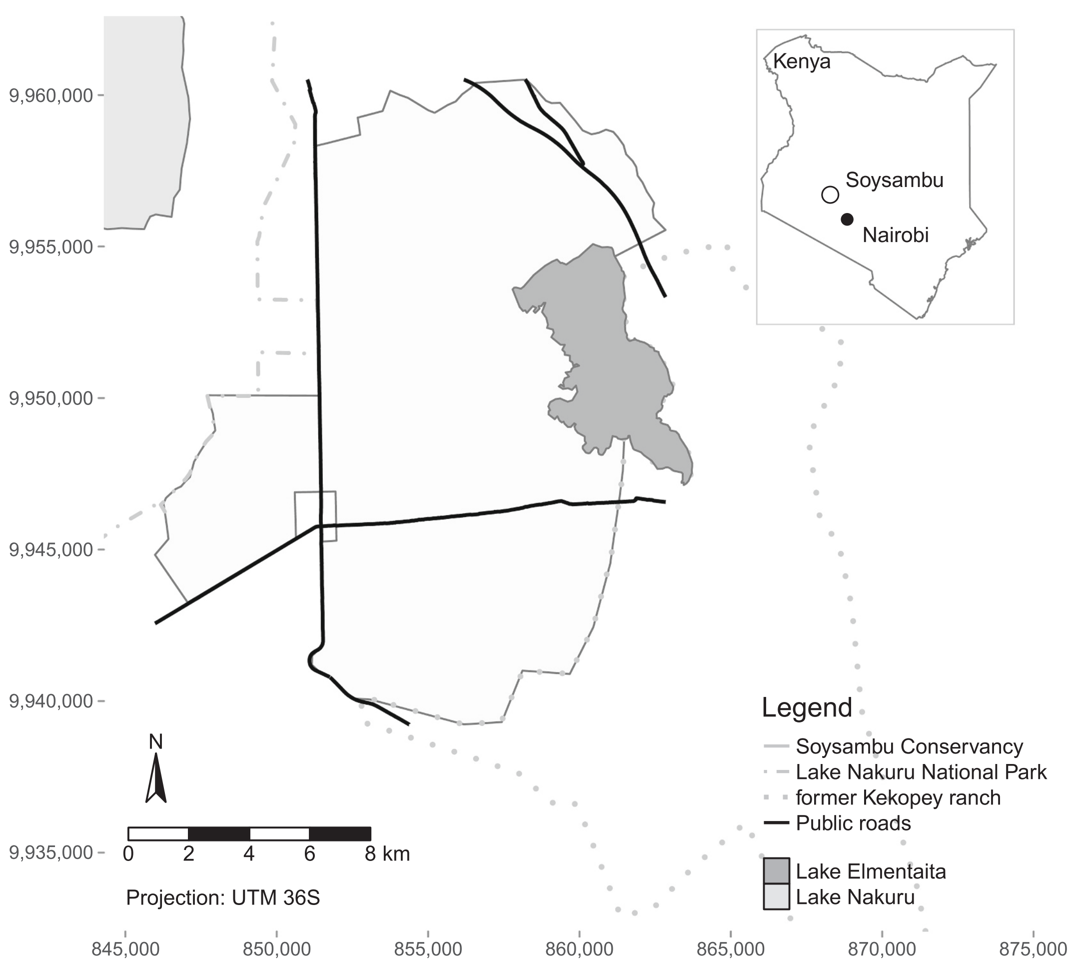


Fig. 1. Location of the Soysambu ranch and conservancy. Inset: location of Soysambu within Kenya.

2. Methods

2.1. Study area

The 190-km^2 Soysambu livestock ranch is situated west of Lake Elmentaita, an alkaline lake in the Kenyan Great Rift Valley (S 0°28.122′ E 36°11.408′, 1776 m + MSL, Fig. 1). Average annual rainfall in the area is between 600 and 700 mm, and temperature ranges between 18.5 °C and 19.4 °C (Ongalo, 2019). Most of the area consists of open bush land, with the bushes consisting of acacia (*Acacia drepanolobium*) and leleshwa (*Tarchonanthus camphoratus*). Lake Elmentaita is inscribed as a UNESCO World Heritage Site (UNESCO, 2017), as a wetland of international importance under the Ramsar Convention (Ramsar Sites Information Service, 2019), and as a National Wildlife sanctuary (Government of Kenya, 2010).

The Soysambu ranch also operates as a conservancy and is home to over 25 species of mammals, including Burchell zebras (*Equus quagga burchellii*), African buffalos (*Syncerus caffer*), Grant's gazelle (*Nanger granti*), Thompson's gazelle (*Eudorcas thomsonii*), waterbucks (*Kobus ellipsiprymnus*), impalas (*Aepyceros melampus*), and Rothschild giraffes (*Giraffa camelopardalis rothschildi*). It is situated on a corridor that connects Lake Nakuru (northwest of the conservancy, Fig. 1) and Lake Naivasha in the south (Ojwang et al., 2017). The conservancy is separated from Lake Nakuru National Park by an electric fence, and further fencing is promoted by the Kenyan Wildlife Service (Soysambu Conservancy, 2020). The Soysambu estate is dissected by three public roads (Fig. 1). The wildlife corridor in the south-east of the conservancy was covered by the former Ututu conservancy. However, this area has been sold, parceled and fenced (Ongalo, 2019), and will be developed as holiday homes (Mutwiri et al., 2017).

Because the Soysambu estate is a mixed farm (livestock and conservancy), it differs in two aspects from protected areas without commercial activity. First, water is available for both livestock and wildlife throughout the estate. No spatial concentration of permanent water points exists at which poachers can place their snares. Second, the livestock operations cause more humans (mainly herders) to be present in the area than would otherwise be the case.

The conservancy employs 65 unarmed rangers responsible for providing security for the estate, inhabitants, visitors, livestock, and wildlife. The rangers work in shifts (6 a.m. 6 p.m., n = 37; 6 p.m. 6 a.m., n = 24). Day patrols are conducted on foot by groups of two to four rangers, assigned to an area within the conservancy. At night, two vehicles patrol the estate, each staffed with a driver and a supervisor. Most of the night-time staff is allocated to park infrastructure, such as gates and stores. The conservancy has limited contact with the surrounding communities, and consequently, few informers are available to help identify poachers or planned poaching activities. The conservancy does not keep detailed records of patrol efforts, but registers poacher sightings in an observation book. The rangers reported eight sightings during the fieldwork research period (January to April 2019).

The rangers regularly remove snares, often with the help of nongovernmental organizations (NGO's) and the Kenyan Wildlife Service (KWS). Desnaring reports from the conservancy show that rangers often return to the same areas, as poachers replace the snares that were removed during desnaring.

2.2. Methodology overview

The methodology was executed in three steps (Fig. 2). We simulated three strategies for the removal of snares in a protected area, based on snare positions known from previously implemented desnaring transects. These desnaring strategies aim to demonstrate that clustered placement of snares can be leveraged to increase the effectiveness of desnaring. We first confirmed that snares are indeed placed in a clustered pattern, and assessed the strength of association between their positions and spatial variables (step 1, Fig. 2). Using these results, we developed a predictive map to reduce the search area using species distribution modeling (SDM, step 2, Fig. 2). SDM has previously been applied to predict poaching activity in both marine (Bisi et al., 2019; Thiault et al., 2020) and terrestrial protected areas (Denninger Snyder et al., 2019; Jenks et al., 2012). In this study, predictive modeling is followed up by desnaring transects to validate the model (step 3.1,

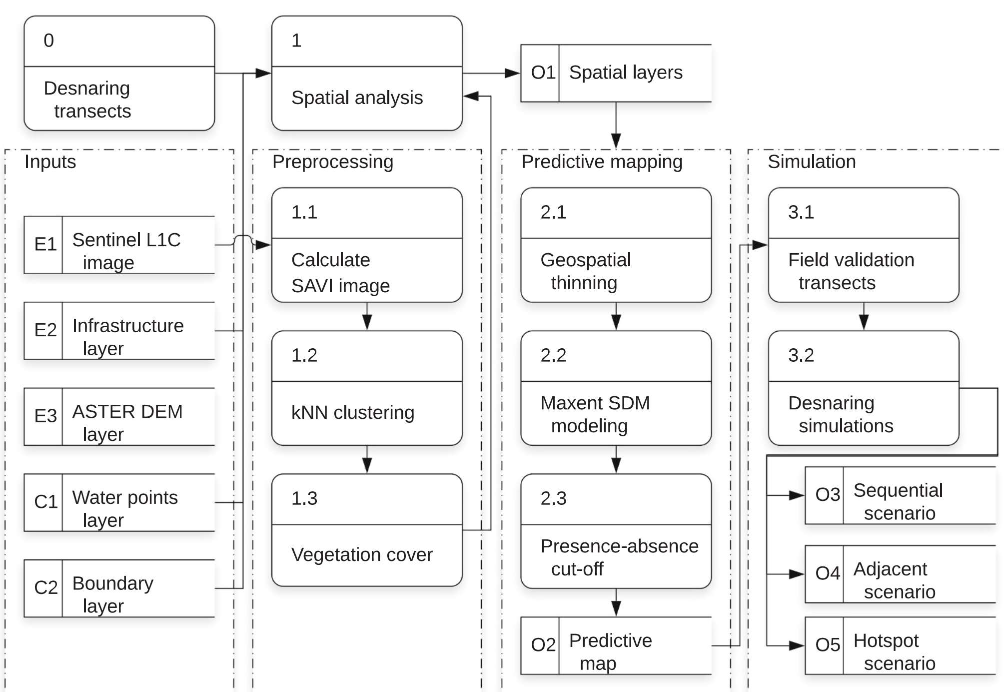


Fig. 2. Data flow diagram for methodology. Inputs are coded as "E" (external data suppliers) and "C" (data supplied by conservancy). Outputs are coded as "O". DEM stands for "digital elevation model", SAVI for "soil adjusted vegetation index", kNN for "k-nearest neighbors", and SDM for "species distribution modeling".

Fig. 2) and simulations of patrolling strategies (step 3.2, Fig. 2).

2.3. Development of desnaring strategies

"Desnaring strategies" are understood here as a set of search actions aimed at maximizing the likelihood of snare detection. The likelihood that an object will be detected may be deconstructed into the probability that it is available for detection and the efficacy of the detection itself (Kéry and Schmidt, 2008). The probability of detecting a snare is thus $p(D|A) * p(A)$, where A is the object's availability, and $P(D|A)$ the probability of detection D, given availability for detection A. From this perspective, the first step in the development of desnaring strategies is reduction of the search area, followed by measures aimed at increasing the probability of detection. The search area is reduced by developing a predictive map into which the spatial analysis results of known snare positions are incorporated. This involves spatial analysis of previously implemented desnaring transects, and field testing of the predictive map with additional desnaring transects to validate the results. The probability of detection is increased by multiple visits to areas where snare presence is suspected. This reduces the probability that the snare will not be detected $\neg P$ to $(1-p)^n$, where p is the probability that a snare will be detected and n is the number of visits to the area.

2.3.1. Spatial analysis of desnaring transects

We analyzed snaring patterns, using a data set containing the coordinates of 308 neck snares that were removed from 82 km of previous desnaring transects. Spatial analysis of this data set was carried out using the statistical computing language R (R Core Team, 2019) and library spatstat (Baddeley et al., 2016). Base maps for this analysis were an ASTER digital elevation model (DEM) (METI, 2011) and a Sentinel satellite image (ESA, 2018).

The analysis aimed to identify the variables that best described the relationship between snare positions and spatial features of the conservancy using the area under curve (AUC) (Jiménez-Valverde, 2012). These variables included distance to public roads, park boundaries, water points, settlements, and infrastructure, such as gates and lodges (Table 1). Additionally, we assessed the relationship between the degree of land cover, elevation, and snare positions. The vegetation cover was assessed through unsupervised k-means classification (Steinley, 2006) of a soil-adjusted vegetation index image (SAVI, Huete (1988)). The gradient from bush patches to open areas (degree of vegetation cover) was calculated by a moving window operation on the land cover image. Finally, we estimated the spatial resolution for further analysis from the distribution of nearest distances between snares.

The clustering properties of snare placement were confirmed using the Hopkins-Skellam index (Hopkins and Skellam, 1954). This index uses ratio A of the nearest distance and empty-space distances of m randomly sampled points. A value of $A = 1$ indicates a completely random pattern, as both distributions are similar in that case; $A < 1$ indicates a clustered pattern. This index was selected due to its low sensitivity to edge effect bias (Baddeley et al., 2016), which crime pattern theory predicts to be substantial (Song et al., 2017).

2.3.2. Predictive mapping of snare occurrences

A predictive map of snare occurrences was produced using Maxent, a presence-only SDM method (Phillips and Dudík, 2008). We selected a presence-only method as snares have a detection probability of 20–40% (Ibbett et al., 2020; Linkie et al., 2015; O'Kelly et al., 2018a; Watson et al., 2013) and can therefore easily be missed during desnaring operations. Predictive modeling was carried out using the R packages dismo (Hijmans et al., 2017) and SDMtune (Vignali et al., 2020). We applied spatial thinning to correct for sampling bias (Aiello-Lammens et al., 2015). This bias occurs when desnaring teams concentrate their efforts on a single area once a snare has been found. The threshold for predicted presence/absence of snares was calculated using the true skills statistic (TSS). This statistic (also known as Youden's J) equals sensitivity + specificity-1 (Freeman and Moisen, 2008). Maximizing the sum of specificity and sensitivity is therefore equivalent to maximizing TSS (Allouche et al., 2006; Liu et al., 2013).

Table 1
Variables used in the analysis of snare occurrence.

Variable	Motivation
Distance to public roads	Crime pattern theory posits that crime hotspots are likely to occur at the edges of land use change (Brantingham and Brantingham, 1993; Song et al., 2017). This has been confirmed by research in protected areas (Wato et al., 2006; Watson et al., 2013).
Distance to park boundaries	As predicted in crime pattern theory, researchers often find snares along the boundaries of protected areas (Loveridge et al., 2020; Mudumba et al., 2020; O'Kelly et al., 2018b; Wato et al., 2006).
Distance to water points	Water scarcity causes animals to congregate regularly around water points, where they are targeted by poachers (Watson et al., 2013).
Distance to human settlements	Offenders will prefer targets that are not further away from their homes than necessary (Summers and Guerette, 2018; Townsley, 2017). This applies to bushmeat poachers as well, since snares must be inspected frequently (Mudumba et al., 2020; Noss, 1998). Correlations between the presence of settlements and snaring locations were identified in spatial snare research (Coad, 2007; Loveridge et al., 2020; Mudumba et al., 2020; Wato et al., 2006).
Distance to park infrastructure	Researchers have found snares or traps near ranger posts in several cases (Jenks et al., 2012; O'Kelly et al., 2018b; Watson et al., 2013).
Degree of vegetation cover	Savanna ungulates which are targeted by poachers will seek shade in the bushes, but will stay close to open areas, so they can escape predators. Transitional spaces from open areas to denser bushes are also areas in which poachers can operate unseen. These are the areas in which routine activity approach would predict a higher likelihood of crime (Felson, 2016). A relationship between snare abundance and vegetation density was identified by O'Kelly et al. (2018b).
Elevation	The relationship between poaching locations and elevation was assessed in snaring (Gurumurthy et al., 2018; Jenks et al., 2012; Linkie et al., 2015), and in trophy poaching (Park et al., 2016; Rashidi et al., 2018; Zafra-Calvo et al., 2016).

The data points were randomly partitioned into four testing and training sets (folds). The SDM model was cross-validated by developing a model from three folds that was tested on the remaining fold. This process was repeated until each fold had been used as a training set. The AUC and TSS statistics were calculated using cross-validation, followed by a field testing. Here, we compared the snare densities found in low and high snaring probability areas. This comparison is tentative, as the sampling effort required to obtain a reasonable statistical power (e.g. $1-\beta = 0.8$) in the analysis of rule-breaking is prohibitive in protected areas (Jones et al., 2017).

2.3.3. Simulation of desnaring strategies

Three desnaring strategies were tested through simulation. The reasons for testing desnaring strategies through simulation rather than field testing are twofold. First, the probability of detecting snares is approximately 20–40%. The chance of missing a snare is therefore greater than finding it. This creates a considerable variability in the results, thus requiring repeat transects to cancel out run-to-run snare recovery fluctuations. These repeat transects would have to be replicated for each desnaring strategy. Second, poachers may either temporarily suspend their activities or displace them to other areas within the conservancy. This effect may be especially pronounced when only part of the conservancy is used to test desnaring strategies. In sum, the required research effort would be lengthy, costly, and wrought with methodological uncertainties due to snare detectability and possible displacement of poaching activities. Our computer simulations circumvented these limitations by repeating desnaring transects many times, thus canceling out variability in individual desnaring runs.

The landscape used in the simulation runs is based on the predictive map of the conservancy, where each raster cell contains the predicted snare occurrence (likely/unlikely). Only cells for which a high probability of occurrence is predicted are visited. Snare positions are based on the results of desnaring transects carried out after predictive mapping described in the previous section, and snare clusters are simplified to a single position.

Each scenario simulates a desnaring team covering a 100-meter wide swath moving through every raster cell for which the occurrence of snares is predicted. We simulated desnaring using both 20% and 40% detection probability. The raster cell size is set based on an analysis of the nearest distance of detected snares.

Detection of snares is simulated by comparing detection probability with a random generated number from a uniform distribution in the interval [0,1] upon arrival of a desnaring team in a cell. The snare cluster is considered to have been detected and removed if this random number is smaller than the detection probability. For example, if the detection probability is 40%, then a random number of 0.39 leads to removal of the snare cluster. Snares are replaced once desnaring moves on to a different cell, and they can then be removed during repeat visits. These replaced snares were tallied separately. The simulated desnaring of the protected area is repeated until the cumulative moving average of the snare recovery rate stabilizes.

The simulated desnaring strategies progressively exploit the observation that snares are placed in clusters. In the first desnaring scenario, every cell is visited only once; this serves as the baseline scenario ("sequential search"). In the second scenario, discovery of a snare cell is followed up by two visits to adjacent cells ("adjacent search"). The third scenario employs hotspot patrolling by framing patrol allocation as an exploration-exploitation (multi-armed bandit (MAB)) problem (Vermorel and Mohri, 2005) ("hotspot search"). Patrols in protected areas are resource-constrained and must therefore balance efforts to discover new hotspots (exploration) with efforts to control existing ones (exploitation) (Qian et al., 2016). Here we apply an ε-greedy policy as an approximate solution for this dilemma (Vermorel and Mohri, 2005). This policy is a natural choice for allocating patrol efforts in protected areas since it pairs simplicity with a performance comparable to more elaborate solutions for the MAB problem (Kuleshov and Precup, 2010). To the best of our knowledge, it was applied for the first time in this context. The strategy consists of comparing, at each simulation step, a random number from a uniform distribution in the [0,1] interval with noise parameter ε. When the random number is smaller than ε, a cell is sampled from snare cell memory. This cell and its neighbors are revisited twice, as in the adjacent search scenario. Desnaring proceeds with a new series of cells if the random number is larger than ε. Therefore, an ε of 1 means that only known hotspots are visited (exploitation), whereas an ε of 0 reduces to the second scenario (exploration), in which most cells are visited only once. The magnitude of ε was set to increase with the number of snares discovered. This results in a shift toward exploration (hotspot patrolling) with increasing numbers of known snare locations.

3. Results

3.1. Spatial analysis of desnaring transects

Poachers place snares in clustered patterns (Hopkins-Skellam index, A = 0.042, p-value < 2.2e−16). Snares were often found in transitions from bushy to open areas (AUC = 0.782), near public roads (AUC = 0.705), and near park infrastructure, such as gates, staff settlements, and lodges (AUC = 0.655). The relationships between snare positions and distance to watering troughs, communities, and boundaries of the conservancy were moderate to low (AUC's of 0.581, 0.551, and 0.507 respectively). The snares occurred within a relatively narrow elevation band (1820–1835 m + MSL), although the strength of this association was found to be weak (AUC = 0.548).

We revisited a desnared area three days after desnaring and found that all removed snares had been replaced. This finding was followed up by three repeat desnaring transects in three hotspots that were known at this point in time. We found that snares were replaced within one to two days after initial desnaring in two out of the three revisited hotspots.

The 95% quantile of the nearest distance between the snares was 254 m. We used a spatial resolution of 250 × 250-meter cells for our predictive mapping on the basis of this observation.

3.2. Predictive mapping of snare occurrence

The results of the spatial analysis were used to develop a predictive map of snare occurrence. The extent to which the Maxent model relied on individual variables (variable importance) is shown in Table 2, and compared with the strength of association found in the spatial analysis.

The cross-validation of the Maxent model showed an AUC of 0.85 and a TSS of 0.59. We validated the Maxent model in the field by carrying out an additional 46 km of desnaring transects (Fig. 3) by comparing low and high snaring potential areas (9 and 37 km, respectively) as predicted by the SDM model. Transects in both areas were set out such that they are comparable in terms of land cover. The snaring densities from these two groups of validation transects were different (Wilcoxon rank sum test, p = 0.04, r = −0.34; low potential areas 0.9 snares/km, high potential areas 2.3 snares/km). Therefore, we concluded that the Maxent model was sufficiently capable of distinguishing areas of high and low snaring likelihood in the landscape to serve as the basis for simulations of desnaring strategies.

3.3. Simulation of desnaring strategies

The snares discovered during the validation transects were used to prepare a map of the conservancy in which desnaring strategies were simulated. The snare discovery performance of the sequential scenario (each cell is visited once) follows a straight line (Fig. 4, left), except for parts of the simulated desnaring transects where snares are discovered. In the adjacent search scenario, cells adjacent to snare discovery sites are visited twice, which increases the snare recovery rate (Fig. 4, middle). Adjacent cells are also searched in the hotspot search scenario, and snare discovery sites are randomly revisited (Fig. 4, right). This results in an increased snare discovery rate compared to the sequential scenario (Table 3), and a concentration of desnaring efforts around known hotspots (Fig. 5).

Desnaring strategies in which adjacent cells are repeatedly visited outperform the baseline scenario in which each cell is seen only once (Table 3). This applies to both removal rates of snares during initial visits (desnaring) and to the recovery rate of replaced snares (resnaring). Replaced snares are not discoverable in the sequential search scenario, because no repeat visits take place. Repeat visits to the same cell are possible, but not frequent, in the adjacent search scenario when search areas in the immediate vicinity of discovered snares overlap. The hotspot desnaring strategy discovers replaced snares more often than the

Table 2
Relationship between variables and snaring positions. The variable importance shows the normalized effect of one-by-one permutation of variables used in the Maxent model. The area under curve (AUC) shows the relationship between snare positions and single variables.

Variable	Variable importance	AUC
Transition bush to open area	0.62	0.782
Elevation	0.16	0.548
Distance to public roads	0.13	0.705
Distance to park infrastructure	0.09	0.655
Distance to watering troughs	NA	0.581
Distance to communities	NA	0.551
Distance to park boundaries	NA	0.507

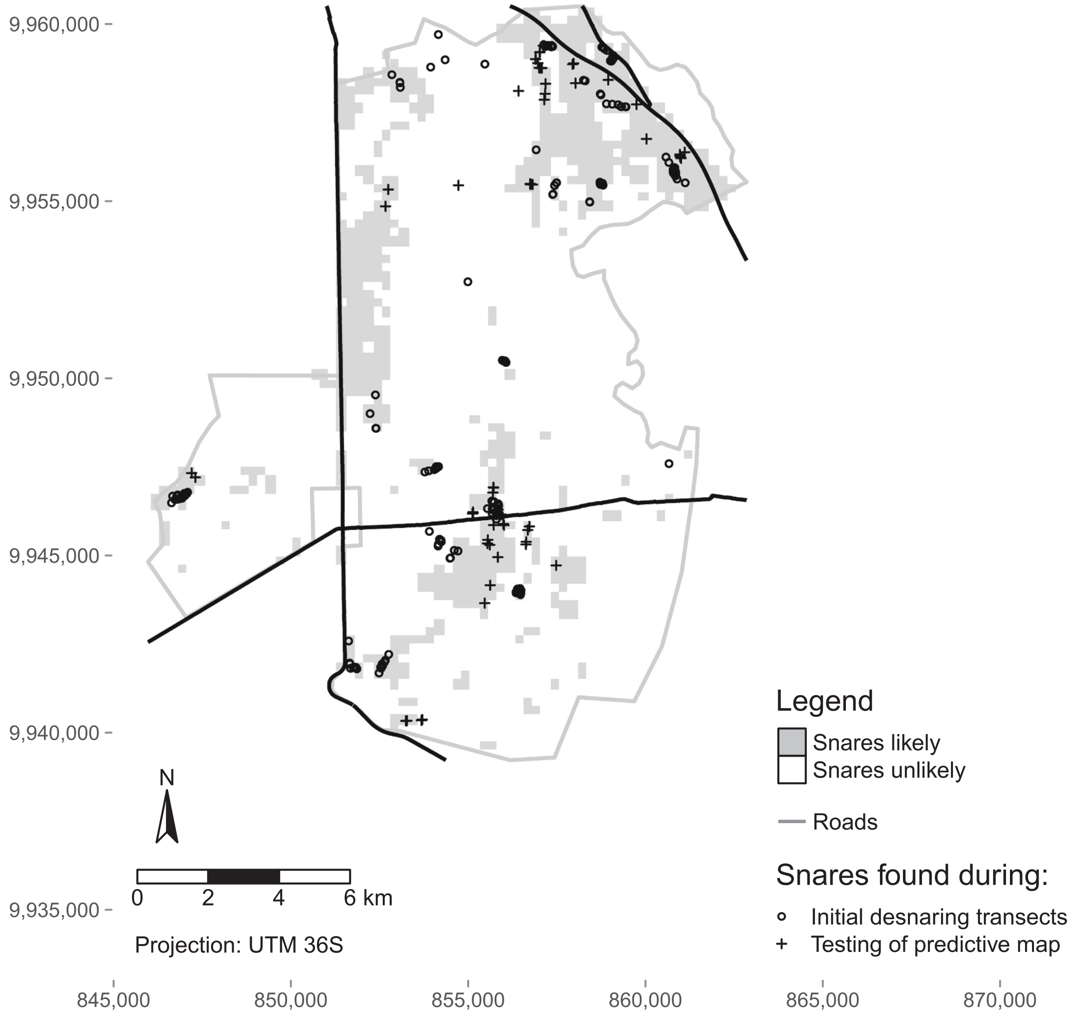
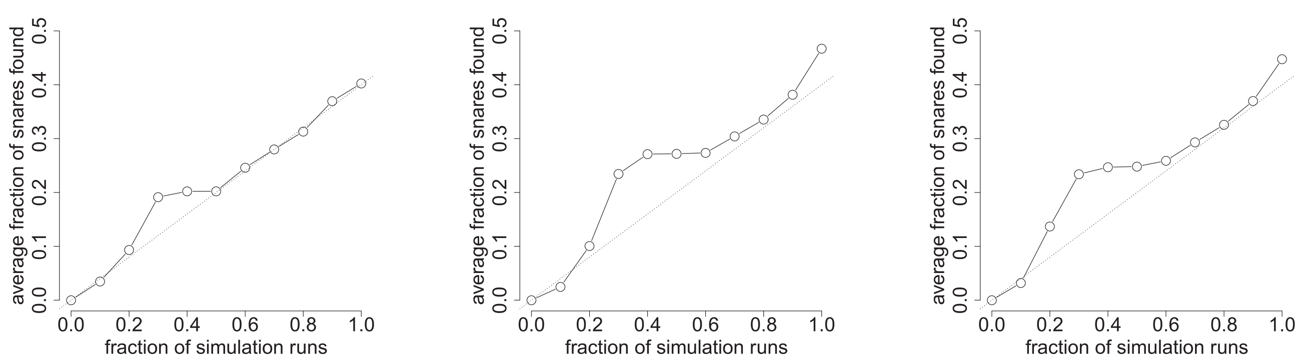


Fig. 3. Predictive mapping of snare occurrence and results of validation transects. Likelihood of snare occurrence on a 250-meter-resolution grid (shaded). Snare positions from both initial desnaring transects and predictive model validation transects are superimposed.



(a) Sequential search (b) Adjacent search (c) Hotspot search

Fig. 4. Snare discovery rates for sequential and hotspot desnaring strategies for 40% snare detection probability. Snare discovery rates in the hotspot scenario (right) increase earlier and more steeply than in the sequential scenario (left). The adjacent search (middle) results in slightly more detected snares than the hotspot search (right), but detects fewer replaced snares (Table 3).

adjacent strategy (Table 3), because the same area will be visited multiple times once snares have been found. Simulation runs with lower probabilities for snare detection rates (20% as opposed to 40% as shown in Fig. 4) result in plots with a reduced slope and less pronounced runs of increased discovery rates. However, the ranking of outcomes for the desnaring scenarios remains unchanged.

4. Discussion

We examined whether the clustered occurrence of poaching events

Table 3
Simulation results. In sequential desnaring ("sequential" scenario), each cell is visited only once and replaced snares are therefore not discoverable. Repeated visits to cells adjacent to snare locations ("adjacent" scenario) leads to occasional repeats of cells that were desnared earlier. Repeated visits to hotspots ("hotspots" scenario) are responsible for the discovery of most replaced snares and finds almost as many snares as in the adjacent scenario.

Strategy	P (detection)	Fraction of area visited	Fraction of snares found	Fraction of replaced snares found
Sequential	20	1.000	0.202	0.000
Sequential	40	1.000	0.402	0.000
Adjacent	20	0.894	0.238	0.008
Adjacent	40	0.825	0.467	0.022
Hotspots	20	0.818	0.230	0.026
Hotspots	40	0.787	0.448	0.040

can be leveraged to improve snare detection in a Kenyan protected area. Our results suggest that the effectiveness of snare removal can be improved by reducing the search area, followed by repeated visits to areas adjacent to snaring hotspots.

4.1. Spatial patterns of snare placement

Snares were found to be placed in clusters ("hotspots"). Such clustered patterns are frequently found in research examining wire snaring (Becker et al., 2013; Campbell et al., 2019), trophy poaching (Kyando et al., 2017; Rashidi et al., 2015), and illegal activities in protected areas in general (Ferreguetti et al., 2018; Wilfred and Maccoll, 2014). A practical consequence of the clustered placement of snares is that the probability of finding hotspots is larger than that for single snares. Desnaring teams slow down the transect upon finding a snare, and examine the area more thoroughly in the expectation that more snares will be found. This implies that the detection probability for the second snare in a hotspot is larger than the first one, that these probabilities are not independent from each other, and that a hotspot may be regarded as one spatial unit.

Snares are often found near roads (Kimanzi et al., 2014; O'Kelly et al., 2018b; Wato et al., 2006) and park infrastructure (Jenks et al., 2012; O'Kelly et al., 2018b). Relationships between snaring and vegetation density (O'Kelly et al., 2018b; Wato et al., 2006), water points (Becker et al., 2013; Kimanzi et al., 2014) and settlements (O'Kelly et al., 2018b) have been established in other studies on snaring. We explain our findings and compare them with the findings of earlier studies from the perspective of environmental criminology, a group of theories that focus on the (spatial) context in which crimes occur.

Snares are placed in clusters to increase the probability of trapping an animal. Poachers must check these snares frequently, as snared animals may break the snare, or be eaten by predators. According to rational choice theory (Cornish and Clarke, 1987), poachers will prefer snaring locations that are not further from their homes than necessary.

Fig. 5. Number of visits per raster cell in the hotspot desnaring scenario. The hotspot approach leads to an increased desnaring effort around discovered snare locations.

This creates a relation between poachers' homes and snare location, a characteristic that can be used for geographic profiling of poachers (Faulkner et al., 2018). Furthermore, crime pattern theory (Brantingham and Brantingham, 1993) predicts that poachers prefer to operate near the boundaries and edges of protected areas, where they are inconspicuous, harder to detect, and where it is easier to elude rangers. This edge effect was found in a range of studies on poaching in Sub-Saharan Africa (Duporge et al., 2020). These associations, however, do not mean that the spatial features themselves cause snaring. For example, not every village surrounding a conservancy may harbor bushmeat poachers, and a road dissecting the conservancy may be a more suitable edge for poachers than the parks' boundaries. Snaring hotspots were found in the vicinity of three out of eight villages surrounding the conservancy. Each of these villages is situated near public roads dissecting the park. A through road can be used to move bushmeat quickly out of the conservancy, and may therefore be a more suitable edge for poachers than the parks' boundaries. A global statistic will, however, show a limited association between park boundaries or settlement locations and snare positions, even when this association is locally high.

The presence of snares in the transition zone from open savanna to bushy areas can be explained by the fact that animals seek shade in bushes while staying relatively close to open areas where they can escape from predators (Thaker et al., 2010); poachers can also operate unseen in these areas. The presence of water points was not associated with snaring. This may be caused by widely available watering troughs in the conservancy. These are placed in relatively open areas and frequented by herders and their livestock.

We found snaring hotspots near park gates, tourist lodges, and an internal settlement. Detection of snares and other signs of poaching activity near ranger posts is not unusual. Among the explanations offered are ranger involvement (Jenks et al., 2012), placing ranger stations strategically in areas with high poaching risk, higher animal density around ranger stations due to the local protection provided by rangers (Maingi et al., 2012; O'Kelly et al., 2018b), different resource allocations between ranger posts (Beale et al., 2018) and a higher likelihood of illegal activity detection, as areas around patrol stations are more heavily patrolled (Maingi et al., 2012). None of these explanations is satisfactory in the context of bushmeat poaching by snaring. First, snares must be inspected frequently, and this requires frequent incursions into the protected area. This progressively reduces the probability that poachers will not be detected, especially when snaring hotspots are situated near park infrastructure. Another relevant observation made by researchers in this context is that often no measurable relation between patrol effort and snaring levels is found (Becker et al., 2013; Campbell et al., 2019; Kimanzi et al., 2014; Wato et al., 2006). We therefore must consider the possibility that rangers detect poachers, but do not attempt to stop them. This explanation for the confluence of ranger presence and snares should be considered within the context in which rangers operate. Over 70% of African rangers have been threatened by poachers or community members, while nearly 70% of them consider themselves to be underpaid (Singh et al., 2020). Moreover, six out of ten African rangers do not think that poachers need to worry about punishment should they be arrested (Belecky et al., 2019). More insight into this explanation of poaching in proximity to rangers is currently unavailable; this presents an opportunity for collaborative research regarding wildlife security. Further research is also required because rangers who refrain from stopping poachers are unlikely to report the observed poaching event. These unreported observations compromise the patrol data that other researchers depend upon to develop predictive poaching models (see e.g. Gholami et al. (2019); Moreto et al. (2015)). Therefore, ranger-collected monitoring data must be approached with care when indications of ranger intimidation or collusion are found. Environmental criminology positions wildlife crime as a social phenomenon in a spatial context, and can help to bridge the gap between social and quantitative research.

4.2. Desnaring strategies

Hotspots are persistent, as the replacement of snares within days following their removal in this conservancy has shown. Therefore, the management of protected areas must balance desnaring and patrolling efforts between known hotspots (exploitation) and the discovery of new ones (exploration). The exploration-exploitation trade-off is ubiquitous and can be found, for example, in animal foraging (Hills et al., 2015) and the design of clinical trials (Press, 2009). The possible application of exploration-exploitation theory in the wildlife security domain has been discussed by Qian et al. (2016) in a more generalized and mathematical form. To the best of our knowledge, a simple policy for approaching this exploration-exploitation problem has not been applied in a protected area before. Our approach consisted of reducing the search area using a Maxent model followed by an annealing epsilon-greedy search policy. Here, patrols revisit known snaring hotspots (exploitation) or search a new part of the conservancy within the reduced search area (exploration). This choice between exploration and exploitation is randomized by comparing a random device with noise parameter epsilon. In either case, discovery of a snare is followed by a more intensive search of the snare cells and their immediate surroundings. This approach has four advantages. First, more snares are found than in a strategy where each cell is visited only once. Second, replaced snares are more likely to be recovered than in approaches where snare cells are not revisited. Third, the random element in both the choice for exploitation or exploration and the selection of the snaring hotspot to be revisited makes this desnaring strategy less predictable for poachers. Fourth, the approach is simple to implement using the programming languages R or Python, or by placing pins in a gridded map on the wall and using a randomizing device (e.g. in Excel).

The hotspot search strategy leverages predictable poaching patterns, namely the clustered placement of snares, the placement of snare clusters near existing hotspots, and the replacement of snares removed by desnaring teams. The stability and predictability of poaching hotspots has been observed in previous research (Critchlow et al., 2015; Gholami et al., 2019). Bushmeat poachers, from their side, can exploit predictable patrolling patterns. In this conservancy, most rangers work from 6 a.m. to 6 p.m., and bushmeat poachers can use this pattern to place snares from 6 p.m. to 6 a.m. when the conservancy is patrolled by two vehicles that can be heard and seen from afar. Poachers may also (correctly) assume that desnaring teams may not return to the same area anytime soon, and that replaced snares will therefore go undetected. Predictable patrolling patterns are regularly mentioned in literature (Herbig and Warchol, 2011; Hötte et al., 2016; Nolte, 2016). The efficiency gains of a hotspot desnaring strategy are offset when possible weaknesses in patrolling strategies or poor ranger morale are not addressed.

4.3. Limitations

Our approach is not without limitations. We have not been able to test our desnaring strategies in the field, owing to the poor detectability of snares, and the possible effect of displacement or temporary suspension of poaching activity. Our simulations repeat transects until the cumulative moving average of snare recovery rates stabilizes, thus eliminating random run-to-run variations. This allows us to predict that hotspot desnaring is, on average, more effective in detecting snares than sequential desnaring. The variability in individual runs means, however, that this cannot be guaranteed for individual transects.

A hotspot desnaring strategy recovers more snares than a sequential search in which sites within the protected area are desnared one by one. However, the improvement is marginal. We concur with Ibbett et al. (2020) that desnaring may not be the best use of resources if it is deployed as a standalone strategy. Our findings demonstrate that studies of snaring patterns require recommendations with respect to how poaching should be patrolled. Thinking about patrolling requires an assessment of the relationship between the deterrent effect of patrols in the protected area and the spatial or temporal displacement of poaching activity. Research hitherto has concentrated on the deterrent effect of patrols (Hilborn et al., 2006; Moore et al., 2018), but there are generally insufficient monitoring data to warrant the conclusion that patrols invariably deter poachers (Dancer, 2019). Our research provides empirical observations of snare replacement, which suggests that desnaring operations do not seem to discourage poachers. We have not followed up these observations with systematic repeat desnaring transects to quantify snare replacement.

This research is site-specific, as desnaring transects, predictive mapping, and simulation of desnaring are all focused on a Kenyan protected area. Other protected areas may find that other variables are more important for the prediction of poaching. However, our methodology is based on the clustering properties of crime, which are well-established in criminological and biological conservation research. Further research may establish whether search patterns can be estimated with reduced preparatory desnaring and modeling. A protected area can, for example, establish raster layers for distances from communities, roads, and boundaries. Each layer may be truncated at a maximum distance value, based either on existing literature or on fresh data. An overlay of these layers and the bushiness (transition from open area to dense bushes) can be calculated, and used as an initial search area. This area can be extended gradually, based on the desnaring results.

5. Conclusion

In summary, the widespread use of snares for bushmeat poaching calls for research into effective methods for removing them. Desnaring is a resource-intensive activity in protected areas that already have insufficient resources. Using a hotspot desnaring strategy based on randomization helps to maximize resource use in these areas while creating patrolling patterns that are less predictable for poachers. Desnaring itself is unlikely to be a suitable standalone policy with which to deter poachers in protected areas.

Data accessibility

Data available from: https://figshare.com/projects/Randomized_hotspot_strategy_Soysambu/88994.

CRediT authorship contribution statement

Henk Harmsen: Conceptualization, Methodology, Software, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization.
Virginia Wangechi Wang'ondu: Conceptualization, Writing – review & editing.
John Nzioka Muthama: Conceptualization, Writing – review & editing, Supervision.
Judith Syombua Mbau: Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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