Size, shape and maintenance matter: a critical appraisal of a global carnivore conflict mitigation strategy – livestock protection kraals in northern Botswana

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Abstract

Fortified kraals are predator-proof enclosures designed to protect livestock at night. Globally, they show great promise in reducing depredation by carnivores, thus promoting co-existence with people. Their efficacy depends on effectiveness, durability, regular use, owner satisfaction, cost-efficiency, and design. We monitored 32 fortified kraals for 18 months in a high conflict area in northern Botswana (*n*=427 kraal months) where lions (*Panthera leo*) frequently kill cattle. Monthly kraal use was 60% and was significantly influenced by kraal type, age, and shape. When used and maintained, kraals stopped livestock depredation. Due to poor maintenance, however, kraal age had a significant, negative influence on kraal use and effectiveness, compromising sustainability and cost-effectiveness. Fortified kraals built by a non-governmental organisation cost US$1322.36 per unit (*n*=20) and mitigated a mean annual loss of $187.32. This suggests cost-recuperation after 7.0 years, or 2.3 times longer than observed kraal lifetime. Conversely, owner-built replicates cost $579.90 per unit (*n*=4), recuperating investment after 3.1years. Owner satisfaction was significantly higher for fortified kraals when compared with traditional kraals. However, owners of fortified kraals did not kraal their cattle more frequently than owners of traditional kraals. Regionally, the mean annual kraaling rate for 29 GPS-monitored cattle herds (*n*=3360 nights) was 40%, leaving cattle vulnerable to depredation, and highlighting the importance of promoting vigilant herding together with kraaling to prevent losses. This combination could reduce regional livestock losses by 80%, or>$38,000 annually, however, kraal fortification alone does not provide a blanket solution to carnivore conflicts in Africa's agro-pastoral landscapes.

Keywords: Conservation intervention, livestock protection, *Panthera leo*, conflict mitigation, efficacy, kraal

1. Introduction

Human-carnivore conflict is a global conservation issue (Inskip and Zimmermann, 2009) with important implications for the persistence of carnivores on nearly all continents (Ripple et al., 2014). In human-dominated landscapes, conflict manifests via livestock depredation (Graham et al., 2005; Baker et al., 2008) or compromised human safety (e.g. Packer et al., 2005). Linnell et al. (2012) identified 24 mammalian carnivores that regularly predate on livestock.

Whilst loss from depredation is usually low in relation to livestock numbers (Graham et al., 2005; Baker et al., 2008), it varies locally and can become economically significant in subsistence communities (Li et al., 2013; Aryal et al., 2014). The attitudes of commercial and communal land users are particularly negative towards carnivores when compared with other damage-causing wildlife like elephants, primates and ungulates (Kansky et al., 2014), even though higher losses may be incurred from disease, drought or theft (Holmern et al., 2006; Tumenta et al., 2013). Intolerance of perceived and actual threats frequently triggers retaliatory or prophylactic persecution of carnivores, contributing to their local, regional and global demise (Woodroffe, 2000; Woodroffe and Frank, 2006; Ripple et al., 2014).

Around the world, conservation stakeholders test preventative, reactive and *laissez-faire* conflict mitigation approaches (see Shivik, 2004; Bangs et al., 2006; Linnell et al., 2012 for reviews of available tools). Conflict prevention can be more cost-effective than lethal carnivore control (McManus et al., 2014). One globally used strategy is the night-time confinement of livestock in fortified, predator-proof enclosures (Mazzolli et al., 2002; Bauer et al., 2010; Lance et al., 2010; Reinhardt et al., 2012; Sapkota et al., 2014; Lichtenfeld et al., 2015) called either "corrals", "pens", "paddocks", "bomas", "stockades", or "kraals". For clarity, we will use the term kraal. Whilst traditional kraals in rural landscapes often merely contain livestock, fortification is necessary where livestock still coexist with free-ranging carnivores. Fortification can be as simple as building strong stone or thorn bush walls from locally available materials (Jackson et al., 2002; Mkonyi et al., 2017). Solutions that are more sophisticated entail portable electrified modules (Reinhardt et al., 2012) or fixed wire mesh constructions (Suttonetal., 2017). Kraaling is a culturally accepted method of livestock confinement and fortification addresses the cause of human-carnivore conflict by safeguarding domestic animals at night. Fortified kraals can be highly successful, reducing the time spent supervising livestock and decreasing nocturnal livestock losses in Africa's communal areas by >90% (Lichtenfeld et al., 2015; Manoa and Mwaura, 2016), sometimes halting predation altogether (Frank, 2011).

Conservationists agree on the challenges of coexistence with carnivores (e.g. effective conflict mitigation), yet there is less consensus on how to facilitate and promote it (Lute et al., 2018). This may be due to a lack of rigorous monitoring of intervention outcomes (Van Eeden et al., 2017). Despite its popularity and widespread use, empirical studies assessing the effectiveness of kraals remain scarce (Okello et al., 2014; Lichtenfeld et al., 2015; Manoa and Mwaura, 2016; Sutton et al., 2017). This hampers comparisons with other conservation interventions (Eklund et al., 2017) and progression towards evidence-based conservation solutions (Van Eeden et al., 2017). Moreover, economic considerations are important in conservation management because optimal use of limited financial resources is paramount (Carwadine et al., 2008; Wilson et al., 2011). Decision-makers depend on accurate costing of conservation activities to assess cost-efficiency (Ferraro and Pattanayak, 2006) as this can determine the most feasible approaches to carnivore conservation (Rondinini and Boitani, 2007; McManus et al., 2014).

Based on our kraal building efforts (20 fortified structures) and 18 months of monitoring of 32 fortified kraals, we provide a comprehensive evaluation of kraal efficacy in a high conflict zone in the Kavango Zambezi Transfrontier Conservation Area (KAZA TFCA), the world's largest trans-frontier conservation initiative that aims to synthesise rural development with sustainable biodiversity conservation. In northern Botswana, lions (*Panthera leo*) inflict high annual livestock losses of between US dollars (hereafter $) $15,700 (2014) and $64,030 (2017) (Department of Wildlife and National Parks, Seronga office). We provide a detailed costing of fortified kraals in this area and determined their effectiveness by comparing livestock losses pre and post kraal fortification, and between fortified kraals and randomised control groups of non-fortified traditional structures. We investigated kraaling rates and drivers of kraal use from 427 direct investigations of fortified kraals and 1 year of livestock GPS-tracking. We determined the variables that influenced kraal use and evaluated kraal maintenance and utility, incorporating owner feedback. Finally, we measured financial and labour investment for this conservation strategy and review its efficacy in light of observed conflict.

2. Methods and materials

2.1. Study area

Our study focussed on communities living at the boundary of NG/11 and NG/12 multi-use areas located along the northern edge of Botswana's Okavango Delta (Fig. 1) in the KAZA TFCA. The study area partially overlaps with UNESCO's World Heritage Site (no. 1000), provides globally important wetland habitat (Ramsar site no. 879), and supports one of the few remaining strongholds of free-ranging lions (Riggio et al., 2013).

The area receives between 500mm and 750mm rainfall annually (Meteorological Services Botswana, 2003; Mendelsohn and el Obeid, 2004). The major dry land habitats in NG/11 are open to dense *Baikiaea-Burkea* woodlands, and mixed mopane (*Colophospermum mopane*) and *Burkea-Terminalia* woodlands on Kalahari sandveld. NG/12 is characterized by seasonally flooded grasslands and reed beds interspersed with riparian forest on islands (Mendelsohn and el Obeid, 2004; Pröpper et al., 2015; Sianga and Fynn, 2017). Floodplains are saturated from February through September, although annual variations occur. The study area comprised five main villages and 44 remote cattle post settlements with approximately 5000 resident inhabitants. The main subsistence activities entail household-specific combinations of agro-pastoralism with small business, and most families subsist on <$500 monthly income. Non-consumptive wildlife tourism in the NG/12 floodplains offers seasonal and permanent employment opportunities.

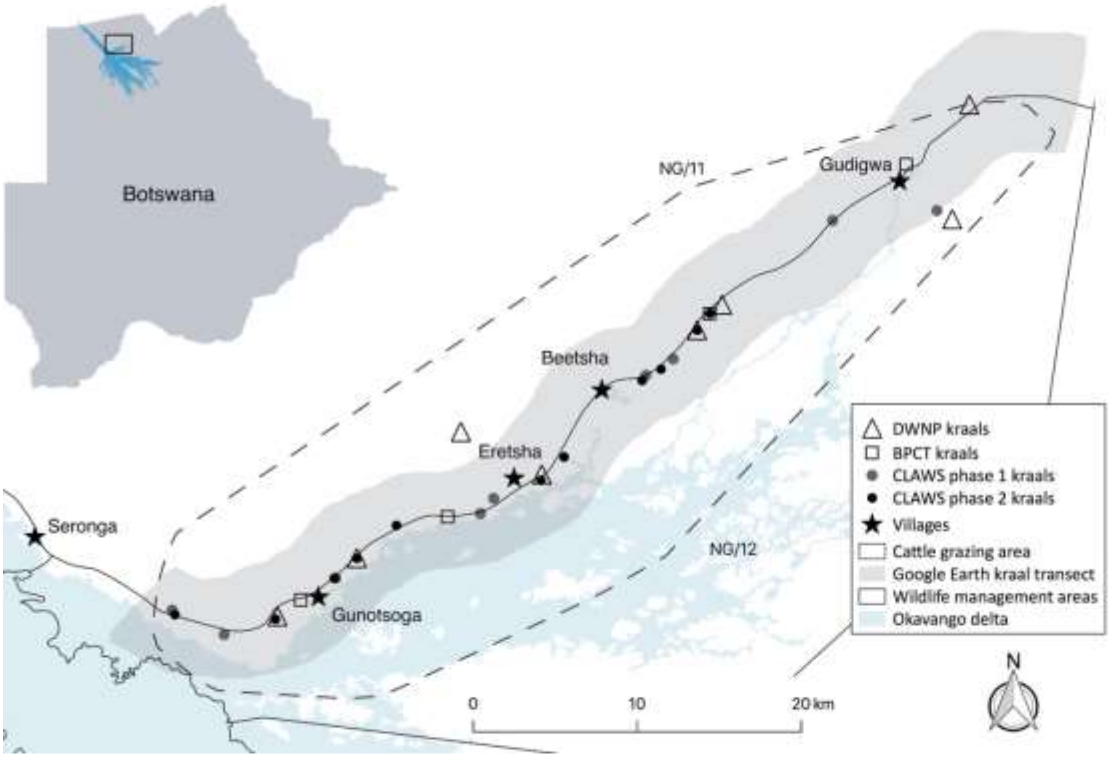

Figure 1 – Map of the kraal study area in northern Botswana showing the locations of main villages, monitored fortified kraals, cattle grazing areas in 2017, and the Google Earth kraal identification transect in relation to the Okavango Delta.

2.2. Livestock management

Livestock is an important socio-cultural commodity and cattle numbers throughout the entire study area increased by 76% from about 6,300 in 2006 to approximately 11,100 in 2017 (Department of Veterinary Services, Seronga office). At least 17 new cattle posts were established since 2006 and median herd size was 36 cattle (range: 2–232, *n*=181) in 2016/2017. Due to veterinary restrictions and the area's remoteness, owners only have irregular market access and sales opportunities. Cattle are mainly managed by their owners and younger family members but are rarely guarded during the day (9.9%, *n*=181). Few owners (4.4%) employ herders responsible for day-time shepherding and night-time kraaling. Others opportunistically confine cattle that are habituated to return to non-fortified traditional kraals (Fig. 2d). Cattle management is haphazard; 59.1% of owners (*n*=107) find and inspect their cattle <3 times per week as herds range freely in unrestricted communal pastures in a Foot-and-Mouth-Disease endemic area (Fig. 1; Suppl. Fig. 1). Human presence near kraals during night hours varies strongly but generally decreases with kraal distance from permanent settlements. There are no artificial livestock water points; cattle depend on seasonally variable surface water for drinking. Herds primarily graze in dry land grass habitats in NG/11 during the wet season (Suppl. Fig. 1a) when seasonal pans provide drinking opportunities. Cattle range significantly farther during the dry season (Appendix 1), grazing in NG/12 wetland habitats (Suppl. Fig. 1b) when seasonal pans in NG/11 dry up and flood waters in NG/12 recede.

Livestock coexist with indigenous ungulates and five resident species of large carnivores, including lion, spotted hyaena (*Crocuta crocuta*), leopard (*Panthera pardus*), African wild dog (*Lycaon pictus*), and cheetah (*Acinonyx jubatus*). Botswana's government compensates predator-induced livestock losses using average market rates for different livestock categories (DWNP, 2013). Owners receive 100% compensation for losses to lions, whereas losses to leopard, African wild dog, and cheetah are compensated at 35% of value. No compensation is granted for losses to spotted hyaena.

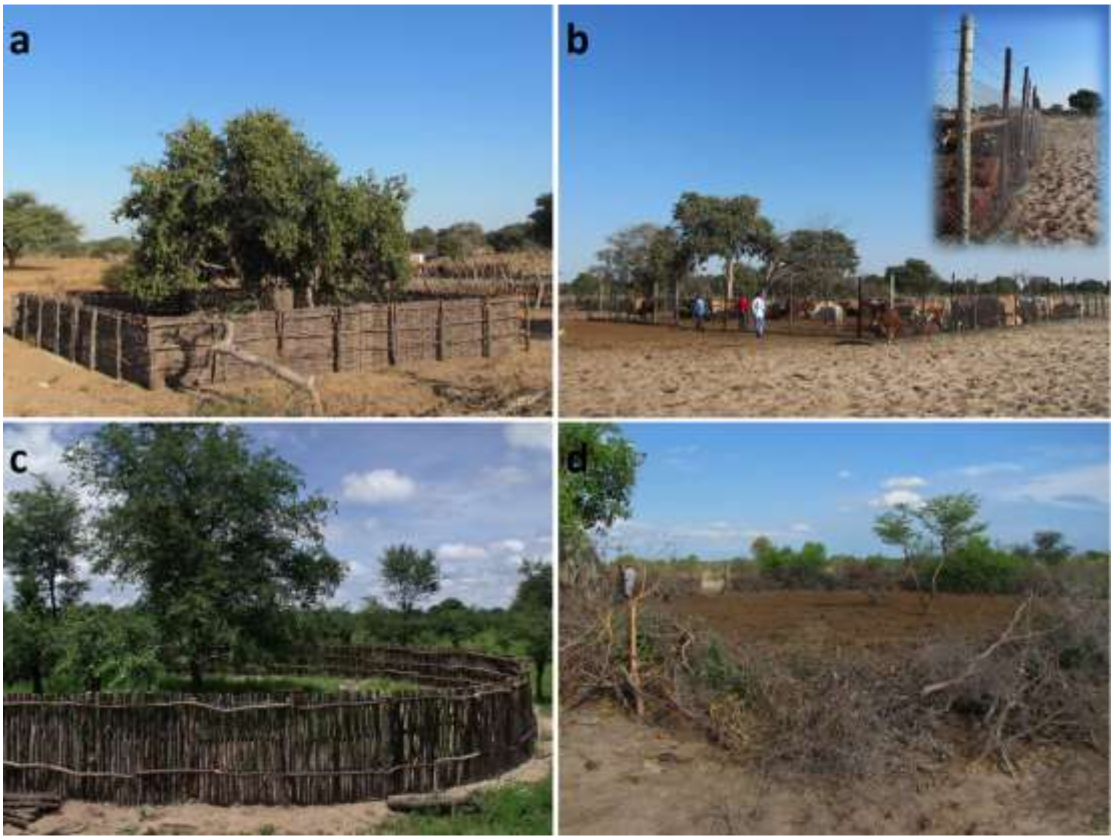

Figure 2 – Kraal designs in the survey area; including a) Botswana Predator Conservation Trust and CLAWS Phase 1 design, b) Department of Wildlife and National Parks design, c) CLAWS Phase 2 design, and d) local traditional kraal. *Kraals in panels a, b, and c were investigated monthly and results compared with a control group of local traditional kraals (d).*

2.3. Kraal construction

Following rampant conflict and lion poisoning in the area during 2010–2013, we built 20 fortified kraals in two phases between June 2015 and September 2017. We monitored these alongside 12 fortified structures previously built by other conflict mitigation initiatives until November 2017 (Appendix 2).

In phase 1 (until February 2016), we constructed eight wooden structures according to the fixed square design of the Africa Centre for Holistic Management in Zimbabwe (Fig. 2a). These kraals measured 12.0m × 12.0m × 2.0m and were allocated to specific owners through community consensus. We built kraals with solid mopane corner and support posts dug 1.0m into the sandy substrate, horizontal support beams, and side panels woven from flexible mopane branches. Panels and beams were joined with 8-gauge wire, the only artificial material utilised in construction. We distributed these kraals (Fig. 1) to provide one fortified demonstration kraal in different villages and cattle posts that were affected by livestock depredation.

During phase 2, beginning in June 2016, we adjusted kraal design and owner allocation. New structures (*n*=12) included one larger (14m × 14m × 2.1m) square, woven-panel design resembling phase 1 kraals, and 11 circular or semi-circular structures of variable size reflecting case-specific livestock ownership (Fig. 2b). We constructed phase 2 kraals in known conflict hotspots (following>100 direct livestock predation investigations), assisting owners affected by predation in the last 12 months. We utilised medium-sized mopane and silver terminalia (*Terminalia sericea*) beams in both horizontal and vertical designs that resembled local kraal designs. We changed to circular shape to maximise kraal area by the materials harvested. Phase 2 kraals included nine new structures, the rebuilding of one phase 1 kraal, and two upgrades of deteriorated traditional kraals. Kraal details are shown in Appendix 2.

Prior to building, we obtained harvest permits for natural materials from the regional forestry office of the Ministry of Agriculture. Mopane trees made up approximately 90% of all materials. We harvested as close as possible to construction sites and with community permission. Owners assisted with material sourcing, transport and construction in several cases. All 20 kraals (hereafter CLAWS kraals) were constructed as permanent structures at the owner's existing kraal location.

2.4. Financial costs

To enable evaluation of cost-effectiveness, we recorded expenses for the 20 CLAWS kraals. Following Weise et al. (2014), we recorded expenses at the time they accrued. We report kraal cost from a non-governmental organisation (NGO) perspective as the total cost per structure, cost per square metre, along with a detailed cost breakdown (Appendix 3). We converted expenses into $ to enable international comparisons, using the mean monthly conversion rate of Botswana Pula to $ in each month that expenses occurred. We classified expenses into mutually exclusive categories:

1) Personnel – including the local building team's salaries, the research manager's salary in proportion to the time spent on kraal building coordination, supervision, and material transport;

2) Materials – including any expenses pertaining to, amongst others, wire, tools, work clothing, harvest permits; and

3) Transport – including any kraal building related vehicle expenses such as fuel for transporting materials and team, vehicle depreciation from wear-and-tear, and tyre repairs.

We recorded each kraal's size, shape, design, GPS location, linear distance from the research station, number of construction days, number of material loads, days spent moving materials, driving effort, and any assistance by kraal owners during the building process. We recorded driving effort for 2-wheel (on-road) and 4-wheel (off-road) operation using the vehicle's odometer. We adjusted fuel expenses to obtain an accurate measurement of fuel consumption in 2-wheel and 4wheel drive operation (100km samples respectively). We multiplied total fuel expense by a contingency factor of 7.5% to account for any kraal-related driving expenses that overlapped with other research activities. To account for vehicle wear-and-tear, we applied a fixed depreciation rate of 2.15 South African Rand per kilometre reflecting Automobile Association (2017) values for our Toyota Land Cruiser 80s series model.

Based on the replication of CLAWS phase 2 kraals by local livestock owners (n=4), we also calculated kraal cost and effort from an owner's perspective. We interviewed owners about their investment into sourcing materials, labour, mode of transport and any other associated expenses. We discounted local builder salaries to the minimum casual labourer wage in Botswana in 2017 ($5.14/day). In all cases, the livestock owner and one family member assisted in kraal construction without remuneration (Appendix 3).

2.5. Monitoring

We employed direct and indirect methods for monitoring kraal use, effectiveness, durability, maintenance, and owner satisfaction. Sample sizes varied as we built new kraals, whilst owners also removed structures. Abandoned and disused kraals remained in the sample that included the 20 CLAWS kraals (Section 2.3; Fig. 2a and c), eight wire mesh kraals commissioned in 2012 by the Botswana Department of Wildlife and National Parks as part of the Northern Botswana Human Wildlife Coexistence Project (Fig. 2b), and four kraals built in 2014 by the Botswana Predator Conservation Trust (Appendix 2; Fig. 2a).

2.5.1. Inspections of fortified kraal use and condition

Between June 2016 and November 2017, we investigated the use of fortified kraals randomly once per month, with at least 10 days between subsequent assessments. To avoid peer-induced bias, we did not inform owners of inspection dates that included public holidays and weekends. We defined use as unambiguous evidence of livestock containment within 7 days prior to inspection, such as livestock presence in the kraal, fresh dung or tracks, and the state of vegetation growth inside the kraal. During the wet season, when indirect signs of use (tracks and dung) may be obliterated quickly, we supplemented inspections with direct observations of kraal use obtained during other project activities. Beyond details of date, time, and observers, we recorded the following information: 1) kraal use (yes or no); 2) condition of walls and gates (see definitions below); 3) presence, numbers and type of livestock contained; 4) availability of permanent shade (yes or no); 5) evidence of carnivore deterrence activities (e.g. guard dogs, protective fires); 6) maintenance efforts (any repairs since last inspection); 7) termite infestation; 8) any structural damage; and 9) any attachments to or structural alterations of kraals. Based on the conditions of walls and gates, we classified kraal condition into mutually exclusive categories, being: 1) '*effective*' (sufficient to contain livestock and exclude large carnivores); 2) '*semi-effective*' (sufficient to contain livestock but not to exclude large carnivores) and; 3) '*ineffective*' (neither effective to contain livestock nor exclude large carnivores).

2.5.2. Analysis of kraal use

To determine which factors influenced the use of fortified kraals, we computed a generalised binomial logistic regression model with a logit link function in program R version 3.4.3 (R Core Development Team, 2008) using the MuMIn package (Barton, 2013). We included the month of the year, owner, kraal size, kraal age, kraal shape, and project as uncorrelated variables ($r < 0.45$) (Appendix 4). We used Akaike's Information Criteria corrected for small sample size (Akaike, 1973; Akaike, 1974) with a maximum likelihood framework to select the most supported model for our data, and used the sum of Akaike's weights (wi) to determine the relative importance of each variable in explaining kraal use (Burnham and Anderson, 1998, 2001).

2.5.3. GPS-monitoring of cattle and regional kraaling rates

To determine accurate livestock kraaling rates, we used nocturnal location data (cropped to local sunset and sunrise times) from 29 cattle herds monitored hourly with SPOT Trace GPS trackers between January 2017 and January 2018. For analyses, we only considered nights with at least six GPS positions per herd (n=3360 nights). We defined a herd as kraaled if at least 66.7% of locations were located within a 4m buffer (i.e. the approximate GPS accuracy error) surrounding the herd's kraal perimeter. We defined herds as 'kraalable' if we found at least one GPS location within 500m of the kraal's perimeter between one hour before and after sunset (n=2961 nights). To assess whether herds were kraaled at different sites, we used the 'recurse' (Bracis, 2017) package in R to compute re-visitation metrics from cattle GPS data. For each GPS location, we calculated the number of additional locations within 30m distance providing an assessment of clusters from which we visually identified areas with high re-visitation frequencies that suggested potential kraal sites. For each herd, we divided the available dataset into progressively moving windows of 30 nights with 14 nights overlap. When clusters did not correspond with known kraals, we visited these locations and recorded any additional kraals. Monitored herds were located throughout the entire study area (Suppl. Fig. 1) and were selected based on stratified, random sampling of the major cattle holdings. Our sample included 11 herds housed in fortified kraals, 15 herds housed in traditional kraals, and three herds in combined traditional fortified kraals. Seven herds had two home kraals of different types (traditional and fortified) and were considered part of the fortified kraal cohort during analyses.

We used a Generalised Linear Mixed effect Model (GLMM) with a binomial error structure and a logit link to study the effect of season, kraal type and herd size on kraaling probability. Based on observed surface water availability during cattle monitoring, we defined the wet season as ranging from January–June 2017 and the dry season from July 2017–January 2018. Herd ID was included as a random variable. We computed GLMM analyses in R using package 'lme4' (Bates et al., 2015).

2.5.4. Effectiveness of fortified kraals and owner satisfaction

To assess the effectiveness of fortified kraals in reducing livestock depredation, we recorded livestock losses to carnivores in CLAWS kraals during 2016 and 2017 and compared these with losses in randomly sampled control groups (n=67 in 2016, n=68 in 2017; Appendix 2) of non-fortified traditional kraals (Fig. 2d).

In addition, we interviewed all CLAWS kraal owners using a semi-structured survey design with open-ended questions. During short interviews we asked owners to state their three main positive or negative opinions about the efficacy and utility of their kraals. We ranked answers in order of priority, assigning weight scores of 3, 2, and 1 in declining order, and grouped common answers. We only initiated interviews 6 months after kraal completion to allow owners sufficient time for opinion formation and experiences from different seasons. During separate interviews, we recorded owner satisfaction scores, on a rank scale from 0 to 10 (0=no satisfaction; 10=high satisfaction), for CLAWS kraals and a randomised control group of traditional kraals at the end of 2016 and 2017 respectively.

2.6. Landscape estimates
To provide accurate landscape estimates of cost and effort for this conservation strategy, we identified active traditional kraals using 2016 Google Earth high-resolution imagery at approximately 200m–500m above ground. We scanned for all identifiable livestock kraals 3km either side of the main road that traverses through all study villages, resulting in a 6km wide community transect (Fig. 1). Kraals were distinguishable from homesteads and agricultural fields by shape, size, and substrate coloration. Subsequently, we ground-truthed identified kraal locations at eight randomly selected cattle posts using direct counts of used traditional kraals and disregarding abandoned ones.

During this study, we also directly investigated 102 livestock predation incidents by large carnivores throughout the study area, for a total loss of 141 cattle, two goats, one horse and one donkey. Our samplereflects40.8% ofall predation incidents (*n*=250) and 49.5% of domestic stock losses (*n*=293; 281 cattle, three goats, three horses, and six donkeys) reported to Department of Wildlife and National Parks for compensation during the same period and area (Suppl. Fig. 2). To estimate potential loss savings from cattle containment in fortified kraals, we multiplied our mean kraal cost and mean work effort with the number of kraals identified from Google Earth and calibrated our regional estimate by observed kraal degradation rates and conflict levels.

3. Results

3.1. Kraal use and maintenance
Between June 2016 and November 2017, we conducted 427 direct use and maintenance inspections comprising 32 fortified kraals built by three different conflict mitigation initiatives between 2012 and 2017 (Fig. 1). Percentage kraal use during the entire study was 59.7% (*n*=255), with a significant difference across sub-samples (Table 1) ($\chi 2=40.596$, $p < 0.001$). Owners used kraals predominantly for confinement of cattle together with their offspring (63.9%, *n*=163), followed by only adult cattle (17.3%, *n*=44), only calves (15.7%, *n*=40), and goats (3.1%, *n*=8). Ten owners (31.3%) attached additional compartments to their kraals because the original designs were insufficient to accommodate all livestock owned. Only 18 (56.3%) of the 32 monitored kraals were used consistently (Table 1). Kraal use significantly decreased with increasing kraal age, dropping below 50% for structures older than 2.4 years (Fig. 3).Nine kraals had already been abandoned or had never been used by their owners (Table 1). Abandonment resulted from owners relocating to other areas (*n*=4), deterioration of structures (*n*=2), inadequate location (*n*=2), and the death of one owner.

Table 1 – Results of 427 investigations of fortified kraals in northern Botswana.

Assessment	Project			
	BPCT* (*n*=4)	DWNP* (*n*=8)	CLAWS* (*n*=20)	All units (*n*=32)
Number of inspections	68	117	242	427
Percentage use	32.4%	38.5%	77.7%	59.7%
Kraal effectiveness				
Effective	2.9%	24.8%	60.7%	41.7%
Semi-effective	35.3%	25.6%	19.0%	23.4%
Ineffective	61.8%	49.6%	20.3%	34.9%
Use frequency				
Consistent (>66.7%)	1	2	15	18 (56.3%)
Sporadic (33.4% - 66.7%)	1	2	2	5 (15.6%)
Abandoned (<33.3%)	2	4	3	9 (28.1%)
Termite damage	48.5%	6.0%	16.5%	18.7%
Shade availability	94.1%	77.8%	93.0%	89.0%
Guard dog presence	10.3%	6.0%	5.8%	6.6%
Deterrence fire	4.4%	8.6%	2.5%	4.5%

*BPCT = Botswana Predator Conservation Trust; DWNP = Department of Wildlife and National Parks, Botswana; CLAWS = CLAWS Conservancy

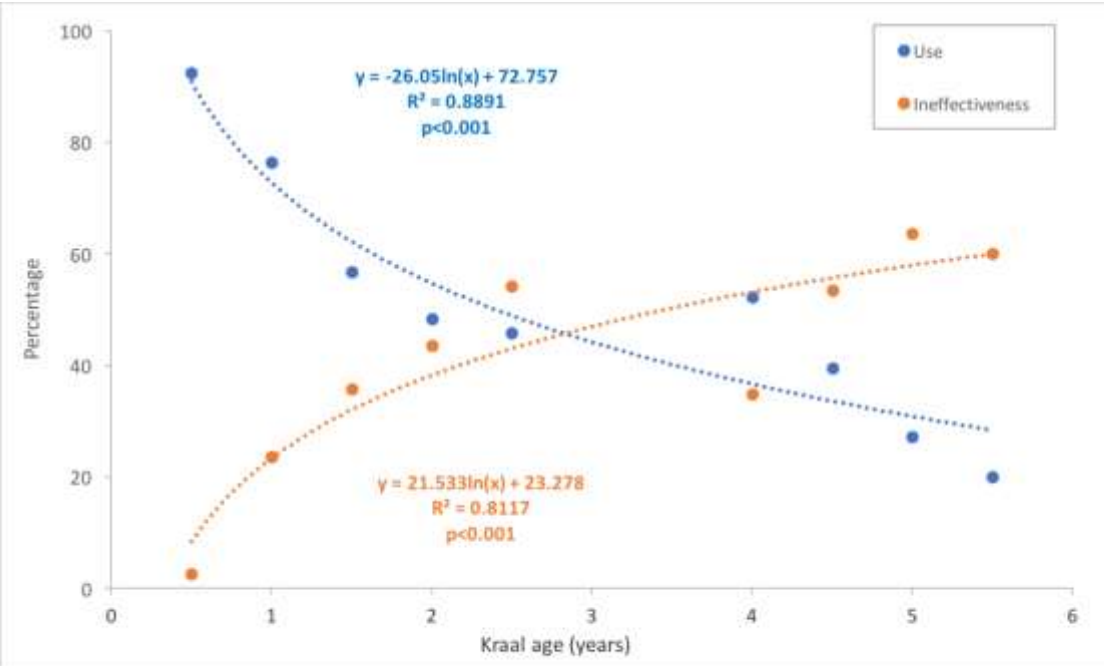

Figure 3 – Effect of kraal age on use and ineffectiveness to contain livestock whilst excluding predators reliably. *Data represent 427 direct investigations of 32 conservation kraals in northern Botswana between June 2016 and November 2017. Kraal age was classified into 6-monthly intervals.*

The regression model including kraal age, shape, and project exhibited most support for observed kraal use (wi=0.31) (Table 2; Appendix 4). These three variables were three times as important as other explanatory variables (Table 2). Round kraals were significantly more frequently used than square ones and CLAWS kraals, those most recently built, were most frequently used (Table 1; Appendix 4). Kraal condition, and thus effectiveness, significantly deteriorated with progressing kraal age, at a similar rate as the decline in kraal use (Fig. 3).

The majority of kraals showed structural damage during inspections, rendering them ineffective against predators (Table 1). Deficiencies mainly resulted from deterioration of natural building materials (*n*=9), wear and tear during use (*n*=4), but also elephant damage (*n*=2). Seven owners (21.9%) improvised repairs that were sufficient to contain livestock but not to exclude carnivores. Despite the availability of natural materials near kraal sites, only seven owners (21.9%) repaired kraals maintaining their original capacity and effectiveness. Low levels of maintenance also manifested in termite infestation of woody kraal materials during nearly 20% of all investigations (Table 1). Our data suggest that kraal utility, as determined by use and effectiveness, diminishes after approximately 3 years (Fig. 3).

Table 2 – Model selection results for the ten most supported models of kraal use. *Variables were not correlated strongly (R <0.45). Quantile-quantile plots for the entire suite of 64 models indicated that variables were normally distributed. Comparing residual with fitted plots provided no evidence of non-linear patterns. Cook's distances were within 0.5 range of the residual vs. leverage plots (see Appendix 4).*

Model	Intercept	Age	Month	Owner	Project*	Shape*	Size	df	logLik	AIC	ΔAICc	w_i
26	0.723	-0.006			+	+		6	-239.398	491.0	0	0.310
28	0.691	-0.006	0.005		+	+		7	-239.157	492.6	1.6	0.140
30	0.740	-0.006		0.002	+	+		7	-239.246	492.8	1.8	0.129
58	0.690	-0.006			+	+	6E-05	7	-239.299	492.9	1.9	0.122
32	0.709	-0.006	0.004	0.002	+	+		8	-239.012	494.4	3.4	0.057
60	0.661	-0.006	0.004		+	+	6E-05	8	-239.072	494.5	3.5	0.054
62	0.709	-0.006		0.002	+	+	6E-05	8	-239.166	494.7	3.7	0.049
25	0.670				+	+		5	-242.474	495.1	4.1	0.040
64	0.680	-0.006	0.004	0.002	+	+	5E-05	9	-238.944	496.3	5.3	0.022
29	0.697			0.004	+	+		6	-242.062	496.3	5.3	0.022
Importance (∑wi)		0.88	0.31	0.33	0.96	0.99	0.29					

*+ refers to categorical variables that are present in the model.

Based on our definitions (Section 2.5.3), we investigated night kraaling of 29 GPS-monitored cattle herds for a total of 3360 nights (mean = 115.9 nights ± 40.7 SD; range: 23–172). Cattle were only kraaled during 1281 (38.1%) of monitored nights, with little difference between seasons (40.4% of dry season nights; 35.5% of wet season nights). Mean annual kraaling rate per herd was 39.8% ± 4.9% SE (range: 0%–94.7%). Two herds were never kraaled. When kraaled, herds were confined in their home kraals during 99.7% of sampled nights. Herds were considered kraalable during 54.6% of monitored evenings (*n*=1617) and were kraaled in 59.2% (*n*=958) of these nights, leaving kraalable cattle unprotected during 40.8% of nights. Herds housed in fortified kraals (*n*=11), on average, were confined during 32.5% ± 7.1% SE (range: 0%–68.3%) of nights whilst herds exclusively housed in traditional kraals (*n*=15) were confined during 43.4% ± 7.5% SE (range: 0%–94.7%) of nights. Herds with combined home kraals (n=3) were kraaled during 48.1% ± 11.0% S.E. (range: 27.5%–65.2%) of nights. The GLMM showed that the probability of a herd being kraaled was not significantly affected by season (wet season: Z=−14.0, p=0.158), kraal type (mixed kraal: Z=0.68, p=0.497; traditional kraal: Z=1.60, p=0.110) or herd size (Z=1.29, p=0.196).

3.2. Kraal effectiveness

Fortified kraals <3 years old prevented livestock losses effectively. We observed no depredation events in the 20 CLAWS kraals in 2016 or 2017. In comparison, randomised control groups of traditional kraal owners incurred a mean loss of 0.61 ± 1.26 SD livestock per kraal in 2016 (n=67; one-tailed t=1.35, p=0.1785) and 0.67 ± 1.39 SD in 2017 (n=68; one-tailed t=1.73, p=0.0432) respectively. Predation in these non-fortified kraals resulted in a mean annual loss of $133.26 ± $304.34 SD (range: $0.00–$1648.34) per kraal owner in 2016, and $99.41 ± $185.14 SD (range: $0.00–$675.96) in 2017 (Appendix 2). Mean percentage stock loss in non-fortified kraals appeared low in 2016 and 2017 (Table 3), but kraal-depredation affected 28.4% and 27.9% of livestock owners in those years respectively, with loss as high as 50.0% of stock owned (Table 3). Considering only livestock owners affected by kraal-depredation incidents (n=19 in each year), mean percentage stock loss was 5.46% ± 0.62% SE in 2016 and 8.78% ± 2.49% SE in 2017, particularly impacting owners with small herds.

Table 3 – Summary of cattle containment and carnivore-induced losses in fortified and non-fortified traditional livestock kraals in northern Botswana.

	Kraal type		
Assessment	Traditional control group 2016	Traditional control group 2017	Fortified cohort
Livestock number			
Sample size	67	68	27*
Minimum	2	3	16
Mean ± SE	55.34 ± 5.09	58.43 ± 5.43	73.00 ± 13.74
Maximum	204	231	376
Annual % loss inside kraal			
Minimum	0%	0%	0%
Mean ± SE	1.54 ± 0.35%	2.45 ± 0.84%	0%
Maximum	10.00%	50.00%	0%
Annual % loss prior to fortification			
Sample size	n/a	n/a	11**
Minimum	---	---	0%
Mean ± SE	---	---	2.38 ± 1.01%
Maximum	---	---	7.35%

* data for abandoned structures excluded

** data only available for CLAWS phase 2 structures

We also compared livestock losses for 12 months before and during use of CLAWS kraals for those owners who consistently used both kraal types for at least 1 year (n=11) (Appendix 2). In the 12 months prior to receiving a fortified structure, these owners lost 12 heads of livestock (mean: 1.09 ± 1.73 SD; range: 0–5) with a total value of $2060.43 in their non-fortified kraals, whereas no losses occurred in the 12 months using fortified kraals (Mann-Whitney U Test: U=33, Z=1.77, p=0.0767).

Fortification resulted in a mean annual loss saving of \$187.32 ± \$272.26 SD (range: \$0.00–\$869.96) per kraal owner.

The only known loss in any of the 32 monitored kraals occurred 2 years prior to this study when lions entered through a broken gate, killing three cattle calves in one incident. Few inspections provided evidence that owners employed additional carnivore deterrence strategies (Table 1).

3.3. Owner opinions and satisfaction

During 2016 and 2017, CLAWS kraal owners assigned significantly higher mean satisfaction scores to their kraals when compared with randomised control groups of traditional kraal owners (Table 4). Asked about their opinions on kraal efficacy, 17 owners (those owning CLAWS kraals for >6 months) provided 45 answers that related to four distinct topics (Table 5). Weighting responses by priority showed that owners considered kraal design as the most important element in their evaluations, including specific remarks on the shape, size and location of kraals, as these influenced kraal utility and practicality. Design was followed by building material considerations that reflected on kraal durability and maintenance, the effectiveness of kraals to safeguard livestock from carnivores, and lastly issues pertaining to livestock husbandry (Table 5). The key concern emerging from interviews was that natural building materials were not considered durable and owners experienced difficulties with maintenance (mostly regarding material transport) and repair (n=9, 52.9%). In addition, five owners (55.6%) of phase 1 fixed-size square kraals specifically commented that these structures were “too small to contain their entire livestock owning”. All respondents mentioned that new kraals “should be built according to the owner's specific requirements, not using standard templates in terms of shape and size”. However, mean 2017 satisfaction scores did not differ significantly between phase 1 and phase 2 CLAWS kraals (U=21, p=0.5157). Ten owners (58.8%) mentioned that they “used kraals less during the rainy season” (November 2016 – April 2017) due to the risk of disease, but we found no empirical support for this statement (Section 3.1). The mean monthly wet season kraal use (November–April) did not significantly differ from the dry season (May–October) (U=16.5, p=0.8728).

Table 4 – Kraal owner satisfaction scores in northern Botswana, 2016-2017.

	CLAWS fortified (experiment)			Traditional, non-fortified (control)			Comparison (Mann-Whitney U-Test)	Probability (one-tailed)
Year	*n*	mean	SD	*n*	mean	SD	U	
2016	9	7.67	2.58	41	3.44	2.08	U = 44.5 Z = -3.5226	p<0.0002
2017	15	8.27	1.53	42	3.69	2.41	U = 43 Z = -4.9201	p<0.0001

Table 5 – Ranked results of owner opinions about kraal efficacy and practicality. *Answers were ranked by priority and reflect opinions from 17 respondents at the end of 2017.*

Statement content	Frequency	Cumulative weight score
Kraal design (shape, size, location)	16	39
Kraal materials (durability, maintenance)	14	27
Livestock safety and protection	10	21
Livestock handling and management	3	6
Others	2	4
Total	45	97

3.4. Kraal costs

Total expenditure for 20 fortified NGO-built kraals was \$26,447.15, with a mean of \$1322.36 ± \$349.52 SD per structure (Table 6). We built kraals at an average distance of 27.5km ± 16.1km from the research station. Kraals averaged 356.7m^2 ± 314.9m^2 SD in size, required a mean teamwork effort of 95.5 ± 25.2 SD work days (range: 41–156 days) and a mean driving effort 355.6km ± 160.2km SD per structure. Kraal cost was highly variable, ranging from \$647.12 for a 75m^2 calf compartment to \$2259.12 for a 1273 m^2 structure able to contain the collective ownership (>350 cattle) of three families (Appendix 3). Average cost per square metre was \$5.82 ± \$2.78 SD. Square kraals (*n*=9) had a significantly higher mean cost (\$8.13/ m^2 ± \$1.14/m^2 SD) than round kraals (\$3.90/m2 ± \$2.19/m2 SD, *n*=11) (U=8, Z=−3.11, p=0.0018) suggesting that round designs can improve area cost-efficiency by >100%.

Due to the intensive effort sourcing and transporting local materials, and construction, personnel costs contributed 88.1% (\$23,310.25) to total kraal cost, followed by transport cost at 7.4% (\$1965.32), and material cost at 4.4% (\$1171.51) (Table 6). Total kraal cost strongly correlated with kraal size (Spearman's correlation rho=0.8032, p < 0.0001) and, due to its direct association with effort, with the team's cumulative number of work days (rho=0.9236, p < 0.0001).

Table 6 – Cost element contribution to construction costs (USD) of 20 fortified cattle kraals in northern Botswana. *Costs reflect expenses by a non-governmental organisation and were recorded between 2015 and 2017.*

Cost element	Total	Mean	Standard Deviation	Standard Error	Minimum	Maximum
Personnel	23 310.25	1165.51	317.15	72.76	562.53	2030.99
Percent of total	88.14	88.09	2.74	0.63	82.97	94.35
Transport	1965.39	98.27	44.46	10.20	18.44	188.90
Percent of total	7.43	7.31	2.54	0.58	2.28	12.01
Materials	1171.51	58.58	18.83	4.32	20.77	97.37
Percent of total	4.43	4.61	1.49	0.34	1.74	7.49
Total	26 447.15	1322.36	349.52	80.19	647.12	2259.12

In comparison, the mean kraal building cost of \$579.90 ± \$405.09 SD (range: \$76.81–\$1096.65) incurred by four local cattle owners who replicated fortified kraals without NGO assistance was 56.1% less than that of NGO-built structures (Appendix 3). Average square metre cost of owner-built kraals was \$0.58 ± \$0.25 SD (range: \$0.16–\$0.80), or 10.0% of the value of NGO-built kraal square metre cost.

3.5. Landscape context

In addition to the 32 monitored fortified kraals, we recorded 382 traditional livestock kraals from Google Earth imagery throughout the community transect. Direct kraal counting (*n*=93) at eight randomly selected cattle posts yielded a 94.6% agreement with those identified via Google Earth (*n*=88). Based on our research, we estimate that approximately 87% of traditional kraals (*n*=332) were not predator proof, requiring significant structural improvement for effective protection.

At a mean kraal construction cost of $1322.36 (Table 6) and a cumulative work effort of 95.5 days for a four-men construction team (Appendix 3), fortification of all traditional livestock kraals in the study area (approx. 750km^2) would require a total NGO-investment of $439,024, and 27.7 years until completion. Considering that kraal utility and effectiveness diminishes after approximately 3 years (Fig. 3), it would require seven construction teams (of four builders each) and two vehicles to fortify all traditional kraals in a 5-year NGO project, whilst also assisting the community with maintenance efforts. Based on the observed mean annual loss reduction (Section 3.2) and building cost (Section 3.4), fortified kraals recuperate investment cost after 7.0 years, thus approximately 4 years after observed deterioration. Conversely, owner-built replicates recuperate building cost after 3.1 years, becoming cost-effective at the time they require first significant maintenance.

Loss claims for livestock depredation by large carnivores throughout the study area (Suppl. Fig. 2) amounted to $72,684.12. Of our direct investigations, 20 incidents (19.6%) occurred at kraals; carnivores entered non-fortified kraals or livestock broke out and were killed in the immediate vicinity (Table 7). Lions were responsible for most kraal attacks (90.0%), the remainder caused by leopard and spotted hyaena (5.0% each). During kraal attacks, livestock owners incurred a significantly higher loss in terms of mean livestock numbers killed ($t=6.766$, $p < 0.0001$) and financial value ($t=2.44$, $p=0.082$) when compared with veldt losses (Table 7). Therefore, despite the significantly lower number of incidents ($\chi2=37.686$, $p < 0.001$), fortification of existing kraals could prevent about 35.2% of livestock losses and off-set 24.6% of the compensation cost (Table 7).

Table 7 – Large carnivore induced livestock losses and associated compensation value (USD) in northern Botswana. *Data represent 102 predation incident investigations between June 2016 and November 2017.*

Category	Incidents	No. of livestock		Compensation value ($)	
		n	Mean ± SD	Total	Mean ± SD
Kraal	20	51	2.55 ± 1.63	7580.40	379.02 ± 238.64
Veldt	82	94	1.15 ± 0.45	23 190.23	282.81 ± 129.32
Total	102	145	1.42 ± 0.99	30 770.63	301.67 ± 161.46

Direct depredation investigations also provided evidence that at least 58 veldt predation incidents (70.3%) occurred at night when livestock were neither kraaled nor guarded, resulting in a total loss of 65 livestock worth $16,971.41. These preventable losses (by effective kraaling) represent 44.8% of investigated livestock losses and 55.2% of the associated compensation value. In conjunction with kraal fortification, therefore, consistent night kraaling of livestock could potentially mitigate 80.0% of all investigated losses, or $24,551.81 (79.8% compensation value). Extrapolation of our sample statistics to all compensation claims throughout the study area across the 18 months of monitoring (see above; Suppl. Fig. 2) suggests that consistent kraaling in secure structures could potentially reduce compensation claims by $38,668.12 annually.

4. Discussion

Fortification of livestock kraals has shown great promise as a carnivore conflict mitigation strategy (Lichtenfeld et al., 2015; Sutton et al., 2017). Indeed, comparison with other interventions supports this, in terms of measured effect (Eklund et al., 2017; Van Eeden et al., 2017) and the opinions of conservation professionals around the world (Lute et al., 2018). Kraals are a valuable and popular tool in many mitigation programs. Our results from a communal agro-pastoral landscape in northern Botswana corroborate that consistent use of fortified structures can significantly reduce night-time depredation by a guild of large carnivores, especially lion. In combination with active herding, kraal fortification has the potential to alleviate financial strain (up to 80%) on the state-funded compensation scheme for predator-induced livestock losses.

Despite this encouraging evidence, our results also demonstrate that fortified kraals are no panacea to livestock depredation. Kraal effectiveness, and ultimately efficacy, depend on consistent use and continued frequent maintenance. In our study area, annual cattle kraaling rates varied by 95% across owners and local maintenance efforts were insufficient to sustain the key purpose of fortified kraals long-term. Less than 25% of owners kraaled consistently, whilst also repairing damage in a fashion that sustained kraal effectiveness. Efforts to kraal were notably lower than in other African agro-pastoral landscapes (e.g. 83% in Kuiper et al., 2015). Fortified kraals were only used 60% of the time and the mean annual kraaling rate of GPS-monitored cattle was 40%. Frequently, cattle were not confined (41% of kraalable nights) even though they returned to kraals without active herding (55% of monitoring nights). There are different possible explanations, including a general lack of motivation to kraal, or, secondly, limited ability as owners may be occupied with other important tasks such as their microbusinesses or the tending of crop fields during the wet season. Kraaling rates did not differ significantly across seasons or between herds housed in fortified and traditional kraals, suggesting the former. A lack of motivation to kraal consistently may be fuelled by the provision of compensation for any livestock losses (except hyaena), although the government compensation guidelines prescribe that livestock need to be safely confined at night (DWNP, 2013). However, livestock owners also reported that it is "increasingly difficult to find reliable young herdsmen as youth either attend school or leave rural cattle posts to pursue more prosperous lifestyles in urban centres". Our conflict records, and those of others studies (Valeix et al., 2012; Loveridge et al., 2017), demonstrate the considerable risk of carnivore predation on unkraaled stray stock at night, especially where livestock coexist with lions. Kraals will only fulfil their purpose if they are used regularly. As this is not the case, the building of fortified kraals alone will do little to address the high levels of livestock depredation in northern Botswana. The cavalier attitudes of most owners towards active livestock protection currently undermine the objectives of the KAZA TFCA as well as those of the national wildlife policy (MEWT, 2013). Considering an increasing livestock population in northern Botswana, more holistic approaches to improved livestock husbandry, including vigilant herding coupled with kraaling (Ogada et al., 2003; Mkonyi et al., 2017) will be required to control future conflict.

This study also highlights that preconceived, standardized kraal designs do not provide a blanket solution. These templates may be easy to budget for and useful for demonstration purposes, yet they do not satisfy owner expectations and requirements. Our results emphasize the need for pilot studies assessing the diversity of livestock ownership and husbandry protocols, allowing for customized kraal building efforts that reflect household-specific circumstances. Switching from a fixed-size square kraal design to round shapes and flexible sizes resulted in significantly higher kraal use and also increased the cost-efficiency of building efforts significantly. Due to the general lack of maintenance, however, NGO-built kraals were not cost-effective. Natural materials deteriorated rapidly and functional kraal lifetime was approximately 3 years, whereas cost-recuperation through loss savings may only be achieved after 7 years of use. NGOs can increase cost-efficiency by focusing kraal building efforts on identified depredation hotspots whilst assisting local owners with transport and materials to encourage replication. Replication was rare, possibly due to un-quantified opportunity costs or resource limitations in terms of hiring labour and material transport. Also, rural livestock owners may not value cattle economically as their access to national and international trade markets is severely restricted. Where it occurred, replication significantly increased kraal cost-efficiency as owner-built structures recuperate investment during functional kraal lifetime. Despite the availability of natural materials in the immediate vicinity of kraal sites, however, the lack of maintenance exhibited by most owners indicates a dependency (i.e. the continued reliance on external assistance) that currently compromises the self-sustainability and cost-efficiency of fortified kraals in northern Botswana.

NGOs have tested different kraal designs elsewhere in Africa, e.g. using wire mesh fencing. These may prolong kraal lifetime significantly, thus improving efficacy. Whilst considered effective at excluding carnivores (Sutton et al., 2017), mesh fencing can also lead to unintended consequences such as serving as a source for snare wire (Becker et al., 2013). Fencing also is expensive and difficult to access for rural communities (Durant et al., 2015). An alternative may be to build kraals as 'Living Walls' by planting indigenous thorny trees (Lichtenfeld et al., 2015). This could address deterioration of materials and reduce maintenance needs, however would require effective sapling protection from increasing elephant (Songhurst et al., 2015) and livestock populations for several years. This expectation appears unrealistic, given the observed lack of maintenance. Our study highlights that conservation practitioners should critically appraise their interventions at pre-defined intervals, utilising reliable monitoring information to evaluate the success of their actions and adjust activities accordingly.

5. Conclusions

Globally, effective livestock protection is paramount to reduce depredation losses and improve co-existence of people and carnivores. Fortified kraals have an important role to play in the conflict mitigation tool box. However, they need to reflect owner-specific circumstances and will only be successful in conjunction with appropriate herding and maintenance. Our study demonstrates the necessity for intensive monitoring to identify the most feasible approaches. We propose that future kraal efficacy assessments need to look beyond livestock losses and incorporate variables such as cost, building effort, designs, kraaling rates, durability and maintenance, as well as socio-economic factors.

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Conflict of Interest:

The authors declare no conflicts of interest.

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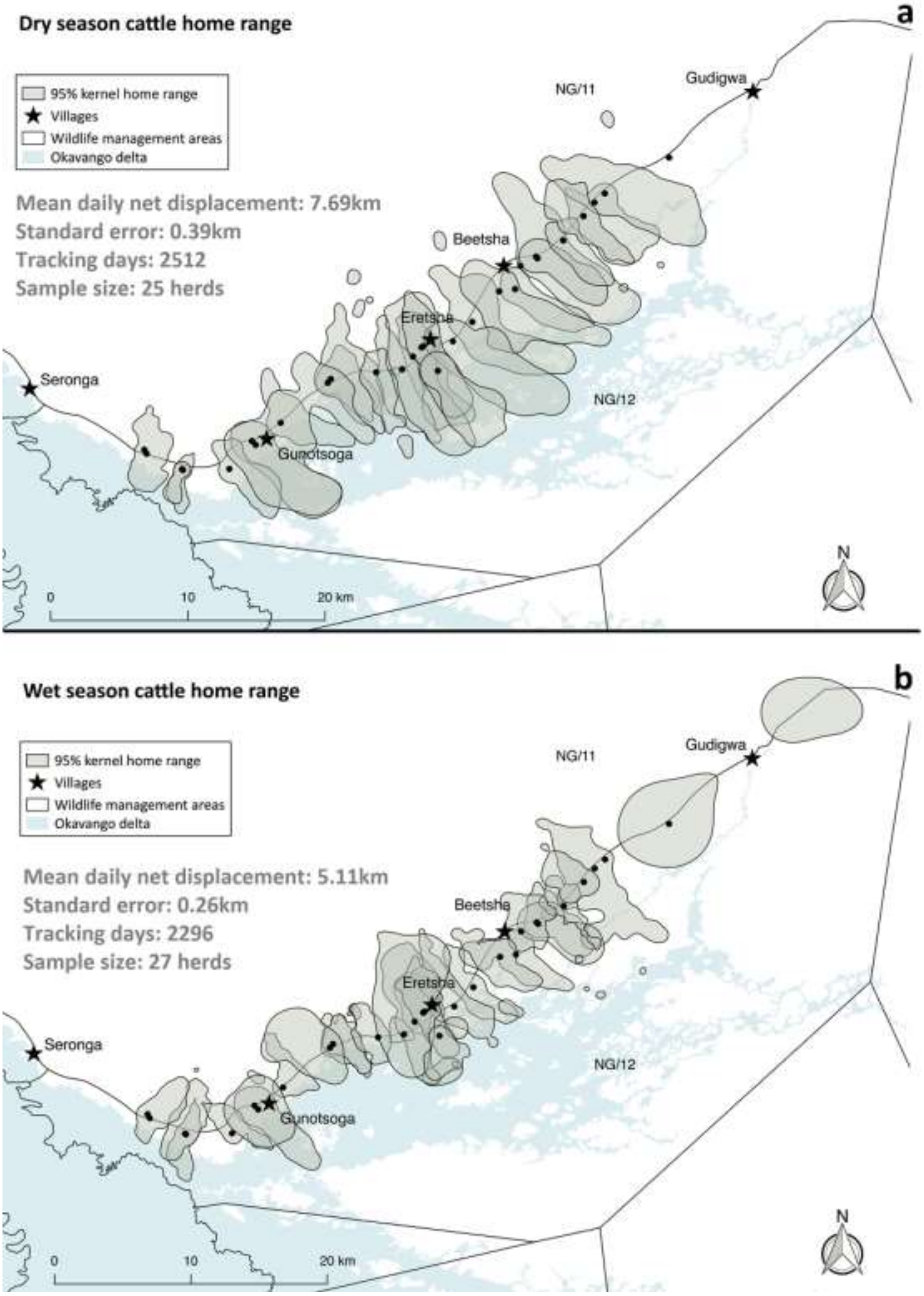
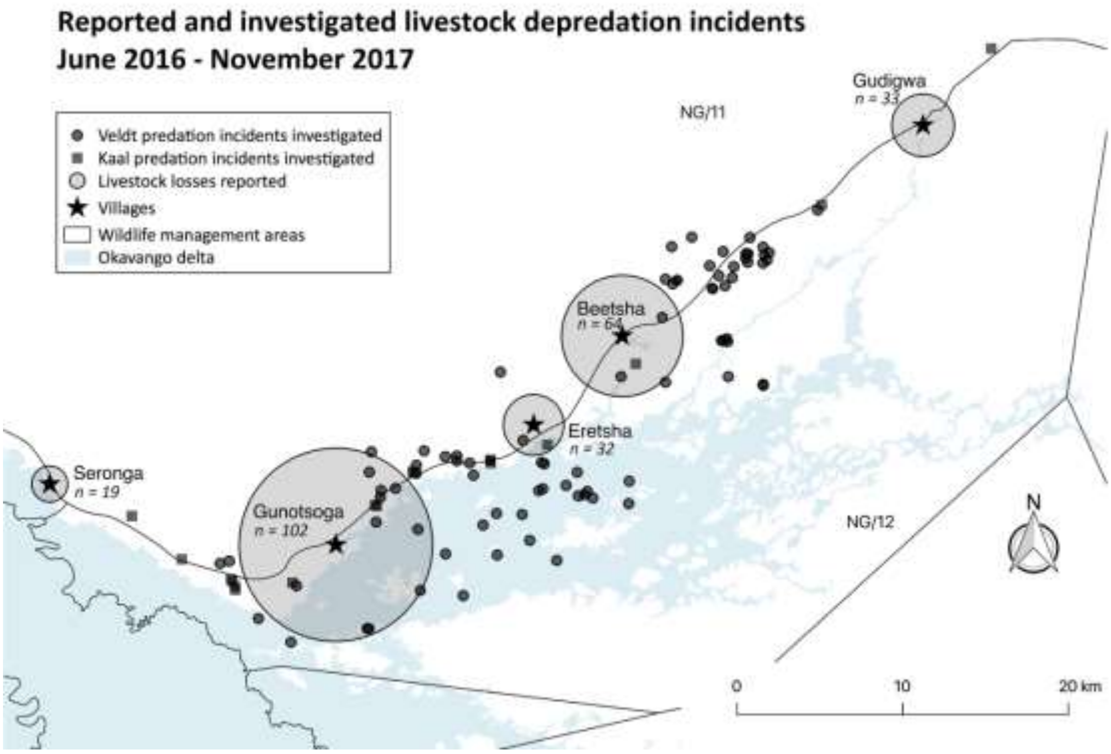
Supplemental Figures



Supplementary Figure 1 – Dry season (a) and wet season (b) cattle ranges computed as 95% kernel density isopleths. *Data represent GPS-tracked movements recorded between January 2017 and January 2018. The wet season lasted from January – June 2017 and the dry season from July 2017 – January 2018.*



Supplementary Figure 2 – Distribution of reported and investigated livestock depredation incidents by large carnivores in the study area between June 2016 and November 2017.