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The Virtual Fence Dynamic: a Breakthrough for Low-Cost and Sustainable Mitigation of Human-Elephant Conflict in Subsistence Agriculture?

Michael La Grange[1†], *Collen Matema*[2], *Bella Nyamukure*[3] *and Richard Hoare*[4*†]

[1] African Wildlife Management and Conservation (AWMC), 27 Victoria Dr, Harare, Zimbabwe, [2] African Wildlife Foundation, Harare, Zimbabwe, [3] 466 Eastview, Harare, Zimbabwe, [4] PO Box CH77, Harare, Zimbabwe

Attempts to deter elephants from entering crop fields and human settlements in Africa have used various barriers (e.g. electric fences, chilli fences, beehive fences or plant barriers), situated on or very near the boundaries of fields or villages, with rather variable success. We explored a very simple new barrier concept based upon re-arranging the layout of foreign stimuli already known to arouse suspicion and fear among elephants. Deterrence involved deploying unnaturally scented objects on and across their pathways of habitual movement leading to crop field clusters. Elephants are suspicious of unpleasant olfactory stimuli, like string or cloth saturated with pungent-smelling chilli oil, old engine oil, or creosote and dislike 'chilli smoke'. Foreign visual items like plastic bottles, reflective metal strips and cow bells possibly reinforced suspicion of these unpleasant scents and influenced the deterrent effect. These flimsy items deployed over very short distances merely acted as a bluff to 'problem elephants' that people were actively trying to impede their progress, and the vast majority chose to turn back or deviate substantially. Thus we coined the term a '*soft virtual boundary*'. We demonstrate that placing virtual boundaries away from village and agricultural lands, forces elephants to encounter them upon leaving their daytime refuges, while still in natural habitat. The suspicion and fear generated here considerably reduces elephants' determination to proceed onwards to risk crop raiding. When multiple, small virtual boundaries are strategically moved around at intervals, a '*virtual fence dynamic'* delivers an enduring deterrent effect. In ten study areas in two countries over seven years this technique led to considerable and consistent reductions in crop damage levels of up to 95% in places. Because these methods (i) completely rely on local knowledge, (ii) were exceptionally low cost and (iii) demonstrated rapid results, the 'buy-in' from affected communities of small-scale subsistence farmers was immediate and very enthusiastic. So this strategy has the potential to remove the most intractable stumbling block to the sustainability of human-elephant conflict mitigation efforts in smallholder agriculture – reliance upon conservation donor funding for very costly and problematic mitigation measures like fencing, compensation schemes and elephant translocations.

Keywords: African elephants, subsistence agriculture, crop raiding deterrence, soft virtual boundary, chilli string, low cost, problem animal control, avoiding donor funding

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Sabrina Dressel, Umeå University, Sweden

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***Correspondence:**
Richard Hoare
rhwildlife@gmail.com

[†]These authors share first authorship

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INTRODUCTION

For more than 25 years human-elephant conflict (HEC) has been widely described and quantified (Hoare, 2012; Chiyo et al., 2012; Hoare, 2015; Shaffer et al., 2019; Sitati et al., 2006; Hoare, 1995; Hoare, 1999a; Hoare, 2001a; Hoare, 2001b). An aspect of it which is seldom mentioned, however, is that the very largely nocturnal activity of crop raiding by 'problem elephants' is often reliant upon them using daytime 'refuges' in which to hide between raiding sorties. In heavily human settled areas refuges are usually patches of dense vegetation like thickets, steep and wooded riverine fringes or rocky hillsides, where natural tree and plant cover has persisted in the landscape due to that terrain's unsuitability for crop cultivation. By contrast in sparsely settled land, the elephant refuge may be patches of largely untransformed natural habitat. And very commonly it may be an officially protected area (PA) for wildlife relatively near or abutting human settlement.

In much of the savanna elephant (*Loxodonta africana*) range in Africa, crop raiding is mostly perpetrated by individual bulls who show 'problem behaviour', either alone or more often in all male groups. Initially this was termed the 'male behaviour hypothesis' (Hoare 1999, Hoare, 2001a) and found applicable to both the African and Asian elephant species (Sukumar, 1990). Subsequently, genetic investigation quantified and supported this hypothesis *via* individual elephant identification using DNA from dung samples in raided crop fields (Chiyo et al., 2011a). This showed that relatively few bulls in a population are 'habitual raiders' and they constitute only a small segment of any local population. A slightly greater number are 'occasional raiders', and the remainder very seldom crop raid or not at all (Chiyo et al., 2011a). A disproportionately small number of individuals perpetrating the majority of human-wildlife conflict (HWC) incidents, is a phenomenon that has been recorded from many problem wildlife species worldwide (Berger-Tal et al., 2015; Blackwell et al., 2016; Barrett et al., 2019).

Several limitations exist to commonly applied barriers trying to prevent elephant access into fields cultivated for subsistence agriculture. For example, electric fences are relatively expensive. The technology definitely works well and in commercial agricultural management situations employing rigorous maintenance, it is easily sustainable. In the subsistence agriculture sector, however, installation is dependent on donor funding, can foreclose other HEC mitigation options and can affect landscape connectivity (Osipova et al., 2018). Donors cannot forever fund and supervise the essential rigorous maintenance and in community-based management situations electric fencing is notorious for failure after a time of early success (Hoare et al., 1998; Hoare, 2015). This is for diverse reasons: theft of solar panels and batteries; disputes from maintenance staff; poor supplies of essential tools or spare parts; inadequate clearance of vegetation contacting the fence line and shorting the current (Hoare et al., 1998). With beehive fences (King et al., 2011) investment is far lower, but donor involvement is still essential to fund the start up. Limitations are habitats that will support sufficiently high densities of bees and also communities who do not have a culture of bee-keeping can be reluctant to adopt the idea. Thus these fences have only shown reasonably good protection over small 'hotspot' areas (King et al., 2017) and not expanded into a very widely applicable crop protection measure. Spiny or unpalatable plant barriers (eg *Opuntia* cacti) have not been widely successful against incursions since plant spines are no real deterrent to elephants. The plants are slow to establish and often grow patchily, thus not forming a strong and consistent barrier (Hoare, 2001b). Many are invasive, alien species to Africa so propagation should not be encouraged.

Chilli was introduced to HEC mitigation in Africa in the early 1990s by Dr F.V. Osborn, who adapted applications used in North America for personal defence against dangerous wild bears (*Ursus* spp.) (Osborn, 2002). The active ingredient of hot chilli pepper varieties (*Capsicum* spp.) is called *capsaicin*, and is an olfactory irritant. The compound when concentrated is most soluble in fats or oils and then referred to as *capsicum oleoresin*.

Chilli string as used in crop protection is merely commercial baling twine or parcel string, very cheaply produced from sisal plant fibre, and smothered with concentrated chilli paste. Chilli paste is made of the crushed seeds of hot *Capsicum* varieties suspended in an oily medium like grease or old engine oil (Osborn, 2002; Karidozo and Osborn, 2015). Home-made chilli 'briquettes' are fashioned from a mix of vegetable matter, elephant dung and chilli paste. They are compressed and dried before being set alight and deployed in braziers, to slowly emit a pungent smoke downwind in the direction of approaching elephants (Osborn, 2002; Karidozo and Osborn, 2015; Pozo et al., 2019). Suspension in oily media makes chilli paste fairly resistant to removal from string fences by rainfall but lines should be regularly checked and replenished when necessary during the wet season.

Low cost chilli string fences and slow-burning chilli briquettes have been well described and proven quite effective in reducing HEC (Osborn, 2002; Karidozo and Osborn, 2015; Chang'a et al., 2016; Pozo et al., 2019) across many elephant conflict zones in African countries. Sustainability issues encountered with chilli methods are mostly the supply of sufficient raw chillies and a cheap enough oily medium available to suspend them on lengths of fencing. After initial training, subsistence farming communities should arrange to grow chillies and prepare their own chilli paste.

A further method of deploying chilli as an elephant deterrent has also proven quite successful. The 'chilli gun' is a gas-powered launcher which fires table-tennis ('ping pong') balls filled with concentrated chilli oil, directly at individual live elephants from close range, when they are actually engaged in problem activity (La Grange, 2020). The fragile balls fracture on impact and the chilli oil sticks to and persists on the elephant's skin for some days. This then acts as a negative experience associated with the location where it was acquired (Le Bel, 2015). Several HEC hotspots in southern Africa in both urban (Scrizzi et al., 2018) and rural settings (CSL Zambia, 2020) have used this method very successfully, the latter for example training more than 20 rangers to patrol nightly and chase problem elephants from fields *via* routine use of the chilli-gun (locally named a 'Mhiripiribomba') (La Grange, 2020). Beams of strong torchlight or loud noises (e.g. from air horns) can be used to teach elephants to associate these stimuli with chilli gun use, and thus act as a future warning to deter persistent problem individuals.

A final use of chilli repellent (a recent and experimental one which was not employed in this study) is mentioned. In an attempt to completely avoid the destruction on 'Problem Animal Control' (PAC) of extremely valuable mature elephant bulls who are especially and repeatedly problematic, they can be darted with immobilizing drugs and treated with more chilli oil on the skin than the chilli gun can deliver. These animals are then woken up again and chased off with disruptive noise (Langbauer et al., 2021). This is termed *'disruptive darting'* - using the immobilization itself to combine with the chilli oil as an extra negative experience and thus deterrent. Early results in preventing problem behaviour (in Victoria Falls, Zimbabwe) are promising (Langbauer et al., 2021).

Many wild animal species recognise spatial variation in anthropogenic risk (Loveridge et al., 2016; Barrett et al., 2019). Because of this and since animals also know their home ranges in great detail, managing some species can make use of manipulating their movements through a so-called 'landscape of fear' (Brown et al., 1999). An illustration of this phenomenon is where some animals show great reluctance to cross lines previously used to demarcate unsafe areas. Examples are black rhinos (*Diceros bicornis*) refusing to move into an enlarged fenced sanctuary; wildebeest (*Connochaetes taurinus*), zebra (*Equus burchelli*) and elephant refusing to move across an old fence line, or a gap opened in a fence line, to where they were previously hunted or harassed - even when highly stressed by chasing with a helicopter (La Grange, 2020). This reluctance can persist for years in some cases. Thus there exists the distinct possibility of manipulating risks perceived by elephants *via* their memory (Burger-Tal et al., 2015; Mumby and Plotnik, 2018; Barrett et al., 2019), through methods based on the 'ecology of fear' (Brown et al., 1999). This was a recommendation from one previous study in Zimbabwe (Guerbois et al., 2012) that largely prompted the current trials we describe.

It is also widely acknowledged that raiding highly nutritious domesticated crops is a choice taken by some individual elephants, especially bulls, to maximize their nutrient intake and thereby gain a fitness advantage (Hoare, 2001a; Chiyo et al., 2011b). This is explained by the biological term 'optimal foraging theory' (Pyke, 1984). Like other problem species, crop raiding elephants are well aware of the risks they are taking (Mumby and Plotnik, 2018) and it is thought this is partly maintained through their cognition which includes memories of danger and human retaliation (Blackwell et al., 2016; Barrett et al., 2019).

Most physical barriers against elephants have been applied at the cultivation boundary, where they tend to remain in place. But permanent, static mitigation measures against HEC can often result in habituation (Mumby and Plotnik, 2018; Barrett et al., 2019) – elephants becoming used to, and thus ignoring them (Hoare, 2001a; Hoare, 2015). We believe this can lead to a zone of habituation to defences around crop clusters. Therefore, the place where crop raiding elephants least expect a challenge is when moving from the comparative safety of a daytime habitat refuge area and travelling towards the riskier territory of agricultural fields (La Grange, 2019).

So in this study we introduce the term 'risk interface' - an area between daytime refuges and crops, in which to place a 'soft virtual boundary' (SVB) (La Grange, 2019). Soft is because it is flimsy; virtual is because it is really a bluff, only erected for a short distance across multiple access routes; and it can be shifted around at different times to create surprise on different routes and pathways (i.e. dynamic). The package of activities in deploying simple bluff deterrents and shifting them around to turn elephants back from agricultural areas and human habitation, and monitoring their effectiveness, can be referred to as a *'virtual fence dynamic'*. This study aims to present evidence that small-scale subsistence agricultural communities certainly can develop capacity to mitigate their HEC problems substantially and sustainably at low cost and in so doing, considerably release their dependence upon the expensive and sporadic support from external donors, which is proving unsustainable.

MATERIALS AND METHODS

Study Areas

The most comprehensive SVB trial data were collected from two very different areas approximately 700km apart: Tsholotsho District in the arid zone sandy soils of western Zimbabwe; and thereafter again quantified in Mbire District, a low rainfall area with multiple riverine terraces in the Zambezi River valley of northern Zimbabwe. Three other districts in Zimbabwe have recently joined the programme, while recent trials also took place in five sites in neighbouring Mozambique, again separated by long distances (**Figure 1**, **Table 1**).

All these districts have elephants both inhabiting protected areas and elephants often residing outside them in unprotected land near human settlements. As most PA boundaries are unfenced, each contiguous local population can usually be regarded as one.

Deployment of the SVB

Community meetings were organised by local government officials in the above rural districts of Zimbabwe and Mozambique, to gauge the intensity of crop raiding and record the position of daytime elephant refuges, plus note in detail the layout of pathways used by elephants to regularly access village cropping areas. Training in the SVB concept, techniques and field deployment was then undertaken (by M LaG, CM and BN) for the relevant employed officials and farmers together.

Across regularly used elephant approach paths in the risk interface, various unnatural objects were placed. The primary type deployed was chilli string with concentrated chilli paste in old engine oil - a previously well described and effective, low-cost deterrent encircling crop fields (Osborn, 2002; Karidozo and Osborn, 2015; Chang'a et al., 2016). Other strong-smelling

FIGURE 1 | Map of elephant range (green) in south-eastern Africa with HEC study sites marked. Zimbabwe sites: 1 Tsholotsho District; 2 Mbire District; 3 Binga District; 4 Hurungwe District; 5 Victoria Falls. Mozambique sites: 6 Limpopo National Park periphery; 7 Moamba District; 8 Maputo Special Reserve; 9 Gorongosa National Park periphery.

liquids applied to the sisal twine were old engine oil alone or creosote (a tar-based wood preservative, **Table 2**).

A roll of parcel string was saturated by placing it in a 5L plastic container containing one of the three liquids. Then sections of about 20m length were dispensed through a hole in the cap, cut off and attached to convenient trees either side of elephant approach paths. In one study area as an experimental comparison, creosoted-treated wooden poles were used to suspend the strings. All strings were suspended at the height of a large bull elephant's face, around 2m above ground, so as to allow unhindered passage of people and livestock beneath them. The total number of strings deployed in each site varied (**Table 2**).

In some string placements other unnatural objects were hung on them: empty plastic bottles with or without reflective metal strips inside; lengths of hanging reflective tape; or small metal bells of the type used by pastoralists to locate their wandering cattle or goats. To bolster the olfactory deterrent properties of the strings, in some places braziers with slow-burning chilli bricks (Osborn, 2002; Pozo et al., 2019) were also strategically placed, allowing the noxious smoke emitted to drift downwind along elephant approach paths.

Data Collection

Local authority employees either called 'resource monitors' or 'community scouts' recorded data on the problem wildlife species that approached chilli string barriers and what reaction animals showed upon encountering them. Crop raiding activity by African elephants is of course predominantly nocturnal or crepuscular, thus often difficult or dangerous to observe directly. But elephant reactions to an unexpected, unnatural intrusion can be deduced retrospectively (ideally early the next day) by an experienced tracker who evaluates animal tracks on the ground and investigates other signs left in the surrounding vegetation like broken branches or crumpled leaves. And community scouts also specifically backtracked to determine the elephants' point of departure (e.g. from a daytime refuge) and their routes of travel. These animal movements and reactions can be broadly classified with regard to proximity of approach to the barrier, rapid or gradual retreat from the barrier, circumvention around the end of it, complete avoidance or direct penetration through or under the string.

The most extensive trial data in Mbire District were systematically recorded using 'KoboCollect' (www.kobotoolbox.org) - an open-source application for storing survey data on mobile phones, originally developed for data collection in humanitarian emergencies. On KoboCollect the following data were recorded by resource monitors: date; refuge location; barrier location; species; number/group size; type of reaction to the barrier - and by how many individuals; direction of subsequent travel.

In the present study a chilli gun was only employed as a last resort to chase away elephants who had navigated through or around the defences employed in virtual boundaries and reached the crop fields. As part of the SVB 'package' this labour-intensive measure is recommended only as back-up, in case the rest of the SVB fails.

TABLE 1 | List of HEC study sites in Zimbabwe and Mozambique.

Country	Site Name	Area*	Trial Peroid	Comment
Zimbabwe	Tsholotsho District	3 Wards	From 2016	Original study site
Zimbabwe	Mbire District	8 Wards	From 2019	Most detailed data
Zimbabwe	Binga District	3 Wards	From 2021	
Zimbabwe	Hurungwe District	1 Ward	From 2021	
Zimbabwe	Hwange District	2 Wards	From 2022	Effectively 'Victoria Falls rural'
Zimbabwe	Victoria Falls urban	1 Ward	2018; from 2021	
Mozambique	Limpopo Nat Park	2 sites	From 2019	Periphery of park
Mozambique	Moamba & Namaacha Districts	1 site each	From 2020	Adjacent to Kruger Nat Park
Mozambique	Maputo Special Reserve	1 site	From 2020	formerly Maputo Elephant Reserve
Mozambique	Gorongosa Nat Park	1 site	From 2022	Periphery of park

**Wards – local administrative subdivisions.*

TABLE 2 | Details of the effectiveness of virtual fence study sites in Zimbabwe and Mozambique.

DISTRICT INZIMBABWE	YEAR	No. Villages	Crop Areaat RiskApprox(Ha)	ElephantDensity (NumberPer Km2)	No. HECReportsPRIOR (Unreliable)	No. HECReportsAFTER	No of String Barriers	OlfactorySubstanceUsed onStrings	Objectson StringsYes/ No	ChilliBraziersUsedYes/ No	Crop DamageReduction	Chilli string success in deterring elephant	Reduction inElephantsShot on PAC	No. PositiveTestimoniesfor SVB (% or total number)	No. ChilliGrowers	
TSHOLOTSHO	2016	20	200	1.5	150	3	10	CH/CR/OIL	Yes reflect	Yes	90%	100%	100% (0 from 14)	>90% (72) farmers	0	
	2017	50	1000 approx	1.5		5	30	CH/CR/OIL	Yes	No	95%	100%	100% (0 from 14)	>90% (137) farmers	0	
	2018	50	1000	1.5			30	CH/CR/OIL	yes	No	90%	80%	1 shot	>90% (184) farmers	0	
	2019	30	1000	1.5			35	SVB in disrepair*		No	Uncertain*	50%*	5 shot*		0	
	2020	20	1000	1.5	15		35	SVB in disrepair*		No	60%*	50%*	3 shot*		0	
	2021	50	1000	1.5	10		35			No	80%	90%	2 shot		0	
	2022	50	1900	1.5			60	CH	No	No				>90% (190) farmers	0	
MBIRE	2019	5	250	1.5				CH	No	Yes	95%		1 shot		15	
	2020	40	6000	1.5			62	CH	No	Yes		97%	0 shot	89 farmers	20	
	2021	48	8700	1.5			20	CH	No	Yes		100%	0 shot	89 farmers	45	
	2022	48	8700	1.5				CH	No	Yes					43	
BINGA	2021	10	250	0.3	30	0	8	CH	no	No	100%	100%	100% 0 shot	95% (40) villagers	0	
	2022	10	250	0.3	10		8	CH	no	No					0	
HURUNGWE	2021	8	1400	0.75		11	44	CH				79%		32 farmers	1	1
	2022	8	1400	0.75										>90% (50) farmers		
VICTORIA FALLS Town	2018	n/a	10	2.0	16 daily	0	15	CH	Yes	No	n/a	100%		All project staff (5)	n/a	
VICTORIA FALLS Rural	2022 so far	22	5600	2.0			15	CH	No	Yes		90% so far	80% (3 from 15)	>90% (150) farmers	1	
DISTRICT IN MOZAMBIQUE																
LIMPOPO Shingwedzi River	2019	4			0	1	OIL	No	No	95%	Yes	Yes	All project staff (7)	0		
LIMPOPO Limpopo River	2020	15				3	OIL	Yes	No	95%	Yes	Yes	All project staff (6)	0		
MOAMBA	2021	2			0	1	CH/CR	Yes	No	100%	Yes	Yes	All project staff (4)	0		
	2022										Yes					
NAMAACHA	2021	1			0	1	CH	Yes	No	100%	Yes	Yes	All project staff (3)	0		
	2022							Yes								
MAPUTO	2020	3			0	2	CR	Yes	No	100%	Yes	Yes	All project staff (6)	0		
	2021				0	1	CR	Yes	No	100%	Yes					
GORONGOSA	2022					15	CH	No	No		Yes					

CH/CR/OIL, Chilli Paste/Creosote/Old Engine Oil.

Limitations on HEC Data

A major limitation of our study is a lack of systematic HEC recordings prior to the placements of SVBs. The diverse reasons for this are common circumstances found in the context of small-scale subsistence farmers facing human wildlife conflicts. Such communities are not in a position to welcome research and experimentation in their areas just for the benefit of relatively well-off outsiders who have the luxury of conducting academic studies. Subsistence farmers themselves are either unable or feel very disinclined to systematically record reliable HEC information, the latter due to not receiving appreciable HEC mitigation support from most levels of authority for many years. Their communities are looking for a rapid solution to a serious livelihood problem and will only participate in any HEC research project if it is both 'mitigation centric' and 'demand driven'.

Simply measuring HEC intensity just by numbers of crop damage reports from farmers themselves is notoriously inaccurate: either significant underreporting or gross exaggeration distorts the true picture (Hoare, 2015). The only reliable system is to physically verify and systematically record details of all HEC reports *via* separate employment of enumerators (Hoare, 1999b). Over large and remote areas with minimal infrastructure and very poorly-resourced institutions, this large undertaking requires levels of funding that are unfortunately not available. And very significantly as research has previously shown, (Hoare, 2001b; Guerbois et al., 2012; Hoare, 2015) poorly-quantifiable social 'opportunity costs' of co-existing with elephants are as important to most rural dwellers as are the more quantifiable damages to their crops.

So it was not always possible to establish fully compatible quantitative data recording systems in each study site. As such our HEC mitigation results have to be judged in ways that can be scientifically unconventional. Various proxies for HEC intensity have to be considered together: conflict report evaluation by project staff (all sites), farmer testimonies (all sites), reduction in control shooting (eg Tsholotsho), expansion of chilli farming (eg Mbire) - in order to indicate the levels we have assigned to SVB uptake and success and crop damage reduction (**Table 2**).

We had the benefit of familiarity with many previous studies quantifying typical patterns of elephant crop raiding and damage (Schaffer et al., 2019; Sitati et al., 2006; Hoare, 1999a), consistently showing these are not proportional to local elephant density calculated from systematic aerial surveys (Dunham, 2015). We also had much experience in judging whether testimonies from subsistence farming communities were genuine and reliable. Testimonies were very closely evaluated by the authors and field project staff whom we trained.

The more quantified sites are reported first from Zimbabwe. Mozambican trials on SVB effects followed some years later when word about their success spread over the land border from Zimbabwe. Much of the implementation in Mozambique was done in 2020/21 without formal training by MLG providing advice remotely during Covid-19 travel restrictions. The two countries local government systems, national language and wildlife management policies are very substantially different. While being employed by NGOs, project staff in Zimbabwe implemented SVBs in close consultation with affected community members and farmers, whereas in Mozambique project staff implemented them with less initial community consultation. There is less quantitative data from the new and much smaller Mozambique projects, but local written reports by officials there confirmed initial results as overwhelmingly positive. With less restricted travel in 2022, joint training courses are now being held to standardize the approach between the two countries.

RESULTS FROM ZIMBABWE

Tsholotsho District

This was the site of initial trials in 2016. To prevent bias in choosing specific fields, a first 'crop cluster' of contiguous fields in one Ward (an electoral subdivision) of the Tsholotsho

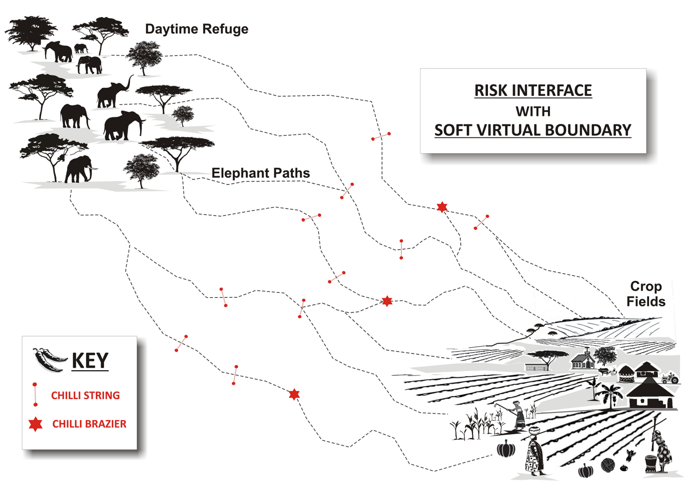

FIGURE 2 | Diagrammatic representation of a virtual boundary arrangement to deter crop raiding elephants.

Communal Land was selected (about 200 Ha). The initial strategy was to set the interventions (chilli strings, bottles, reflective tape strips and bells) in a 'staggered' format on elephant pathways, reasoning that should problem elephants navigate through one of them, they would invariably bump into others (**Figure 2**). Collectively these interventions, it was hoped, would provide a 'virtual boundary effect'. The first trial had very little funding so the strings were deployed over a front of only 2 Km, encompassing a number of closely concentrated regular entry points into the crop cluster. In this study area district officials decided to show the farming community a SVB intervention looking more like a conventional fence, so instead of only using trees as supports, a number of creosote-treated wooden poles were also used to suspend the strings.

Results were unexpectedly successful: the entire cropping period from Dec 2015 to July 2016 in Ward 7 of Tsholotsho recorded no elephant penetration through the new SVB interventions. Elephant spoor indicated animals approached the barriers on several evenings but doubled back when they saw or smelt the various deterrents.

During the main crop harvest period in the months April and May 2016, it was estimated that hundreds of elephants were moving around and even residing within a few hundred metres of the new virtual fence (the adjacent Hwange National Park is home to very high densities of elephants). But the most surprising result of all was that almost the whole of this local population soon avoided the entire interface between the wildlife area and the crop cluster over a total distance of 22km – thus even avoiding the remaining 20km boundary which had no interventions whatsoever.

This unexpectedly widespread avoidance was quantified *via* only three crop lands being damaged in the Ward in 2015/16, inflicting less than US$1 000 damage. In stark contrast, during the previous season (2014/15), without the SVB interventions, many crops were ravaged: 150 cropped lands suffered destruction amounting to an estimated loss of US$22 000 (Rural District Council unpublished report data – **Table 2**).

Also no elephants were shot on official 'Problem Animal Control' (PAC) in the entire Ward 7 in 2015/16. In the previous 2014/15 season the wildlife authorities had destroyed 14 elephants in Ward 7 on PAC, six of them opposite the 2km zone where the new interventions were now deployed (**Table 2**).

Later trialling showed that the avoidance pattern was the same whether old engine oil, creosote or chilli pepper and oil was deployed as the olfactory repellent. Thus different scent types appeared to be equally effective, as long as they were foreign to elephants. Over the subsequent three growing seasons elephants failed to penetrate even the first line of original intervention protecting this crop cluster. But by now a few elephant groups widely circumnavigated the cluster and occasionally approached crops from the opposite side some 5km away. When detected raiding, the chilli gun was used successfully to chase these animals out of the fields on six occasions.

Mbire District

Throughout eight wards in the Mbire District chilli-strings were set at 82 positions, strategically ambushing approach pathways well before crop clusters. Positions were closely monitored over two crop seasons - 2019/20 and 2020/21 - providing 176 observations of animal approach by four species: elephant, hippopotamus (*Hippopotamus amphibius*), spotted hyaena (*Crocuta crocuta*) and kudu (*Tragelaphus strepsiceros*).

There were a total of 32 chilli string positions which elephants approached with intent to cross, and at 31 of them (97%), they did not proceed, either substantially changing direction or turning back. In the very rare cases when they did cross, they deviated away from the crop clusters. Significantly, there were no cases of elephants having navigated closely around the chilli strings and directly moving back to their habitual pathways.

When this data set was evaluated by around 70 community scouts in the whole Mbire District they rated 140 out of 151 observations (93%) as effective; in 4% of cases they were unsure and only 3% did they rate as not effective. Ninety three observations indicated no direct sign of activity. But these very experienced and observant community scouts were so convinced of the success of the SVB technique against elephants that they were adamant many of these 'non-visits' were in fact very likely 'avoidance' well before the chilli-string positions. Although not subject to a controlled trial, these scouts also maintained that chilli strings previously deployed statically on crop field boundaries were far less effective than those now deployed as SVBs in the risk interface, well away from fields.

Binga District

In mid-2021 chilli barriers were deployed successfully in five sites in three wards in Binga. In one site a dam acting as a community water source would have been dry at the height of each dry season due to elephant drinking activity. But after this SVB intervention elephants did not visit either the dam, nearby irrigated community gardens or storage granaries in the villages in the immediate area.

Hurungwe District

ChilIi string SVB barriers were set up around crop clusters in one Ward in 2021. There are very positive testimonies after the last harvest season.

Victoria Falls Town

Highly habituated bull elephants that frequently roam around the town regularly crossed a busy main road to reach the municipal rubbish dump and sewage ponds, where they caused infrastructural damage. An average of 16 elephant bulls have been regular scavengers at the dump and at least five have suffered the suspected fatal effects of plastic refuse ingestion (Le Breton, 2019).

Some half a kilometre from these municipal installations a set of 15 chilli strings was placed across elephant approach paths on the protected area refuge side. Close monitoring with datasheets recorded an immediate effect: all elephants either turned back or deviated far away from the dump for the first two weeks. They did not seek out an alternative access route for the following eight months until the dump was electric fenced and SVB monitoring ceased. But after about a year the electric fence suffered vandalism, theft and poor maintenance, due to which its effectiveness as a protective barrier to both people and animals then failed. The original SVB site has now been re-instated.

Victoria Falls Rural

Outside Victoria Falls town (called Victoria Falls rural but officially part of Hwange District, **Table 1**) there is a mosaic of large protected areas acting as elephant refuges with intervening patches of small-scale farmland that suffer regular elephant raids. Chilli strings have recently been deployed at well-known elephant approach paths where their effects are easily monitored. Problem elephant deterrence in the peak of the 2022 crop season is reliably reported and evaluated as immediate, widespread and almost total. An additional observation was noted whereby chilli strings placed along a cutline through natural forest vegetation produced continuous avoidance up to 5km further along it, where no chilli strings were present.

RESULTS FROM MOZAMBIQUE

Limpopo Nat Park

Up to 100 elephants spent around three months in a riverine area of the park but were intent on leaving during harvest time to continue downstream to raid crop fields, as they had regularly done for years previously. In 2018 a single chilli rope with hanging bottles was deployed in the main path of this mass movement to try to prevent it. It held all but five elephants back successfully (Billy Swanepoel, Peace Parks Foundation, pers comm 2018). In a second trial along the Limpopo River, a herd of African buffalo (*Syncerus caffer*) were prevented from leaving their favoured riparian woodland habitat and proceeding inland to raid crop fields, simply by a length of chilli string suspending reflective plastic bottles being placed across their favoured pathways. This intervention was successful for an entire cropping season (Billy Swanepoel, Peace Parks Foundation, pers comm 2019).

Moamba and Namaacha Districts

Rope with reflective tape was deployed in two HEC hotspots for two months of the maize harvest season. Numerous ‘incursion attempts’ by elephants were reported by farmers but these did not result in any crop damage. No other deterrent method was used.

Maputo Special Reserve Boundary Farms

One location was identified as an area with recurrent HEC events and serious damage to fields. The SVB mainly consisting of reflective tape on chilli strings was in place for four weeks of the harvest season in 2020, during which no conflict incidents were recorded, despite several attempts by elephant herds. In this site it was suspected that light from torches and an air horn blasting also helped on occasion to deter herds that were approaching the fields. On one occasion elephants chose to knock down the electric fence of the MSR boundary instead of using their pathways across which the chilli rope with reflective tape was installed.

Gorongosa National Park

One boundary of this park is a large river with extensive floodplain cultivation on the opposite bank. As such there has been an intractable HEC problem with various mitigation measures tried over many years. The authorities are trialling SVBs in 2022 and we await results after the current crop season.

In the very marginal agricultural areas such as those in this study, communities are so poor they may even have limited access to enough spare plastic bottles, and many being non-pastoralist, don’t own many bells for domestic livestock. Therefore chilli string alone was strongly favoured as the basic elephant deterrent in Zimbabwe and its rapidly demonstrated success diminished the enthusiasm for hanging additional objects on these strings. Reflective tape on chilli string or rope was successful in the trials in southern Mozambique.

DISCUSSION

After several decades, evaluation of the very variable success of most HEC mitigation methods for subsistence agriculture, has shown that they are really neither financially nor ecologically sustainable. Our initiative was trialled in so-called HEC ‘hotspots’, indicated by patchy previous data but many reliable anecdotal reports, where farmers and local government officials were desperate for innovative HEC mitigation. We believe that the combination of qualitative and quantitative results we achieved (**Table 2**), add up to well-demonstrated deterrence of problem elephants which is both rapid and persistent, reinforced by reliable positive evidence from those people affected.

A virtual fence dynamic is a promising cost-effective and sustainable development in HEC mitigation yet to emerge in the very poorly-resourced subsistence agricultural sector in Africa. Aside from the primary objective of a low cost and sustainable method to reduce crop damage, if the virtual fence concept becomes widely accepted and proves successful, there are some persistently problematic and costly issues in HEC mitigation upon which we believe it could have a further very positive influence. Firstly, it could greatly reduce the wasteful and ineffective use of lethal control shooting of elephants that is still widely practiced. Secondly, it could discourage further adoption of expensive electric fence projects that frequently fail due to poor upkeep. Thirdly, it could much reduce the adoption or continuation of official monetary compensation schemes which have proven unsustainable. And lastly, governments could abandon policies promoting translocation of problem elephants – since frequent failures in both Africa and Asia have demonstrated that the problem, being behavioural, is simply moved with the elephant (Fernando et al., 2012). Conceivably in addition, reduction in HEC might also reduce its link to some rural communities’ tolerance of ivory poachers infiltrating their areas (Masse et al., 2017).

Up to now chilli string fences have been deployed on field boundaries, and often adjusted each season by farmers to encircle their variable cropping areas (Karidozo and Osborn, 2015; Chang'a et al., 2016). Whilst they have been reasonably successful, we consider the area surrounding crop clusters and fields can easily become a 'habituated zone' where persistently raiding elephants can perceive weak defences and breach them. Problem elephants display a predictable seasonal pattern of crop raiding whereby they become far bolder as crops mature towards the harvest season. Habitual raiders will ignore various 'traditional defence measures' employed by poorly-resourced subsistence farmers like setting fires, shining lights or generating loud noises from banging metal objects or cracking whips at their field boundaries (Hoare, 2001b). And when strongly motivated by great dietary temptation near rich food sources, some elephants' previously cautious behaviour displayed back in the risk interface can dramatically change, even to direct intimidation and aggression towards humans trying to evict them. Thus around harvest time both crop losses and danger to rural farmers are at their highest levels.

The SVB is a simple strategy merely adjusting known concepts and techniques in innovative ways to influence the natural behaviour of elephants as one of the world's most intelligent mammals. The use of capsicum oleoresin paste on static strings, in burning bricks and in chilli ball guns has definitely reduced elephant crop raiding activity in many, diverse community farming locations in Africa over the last three decades (Osborn, 2002; Karidozo and Osborn, 2015; Chang'a et al., 2016; La Grange, 2019; Pozo et al., 2019; La Grange, 2020).

In simple terms our SVB is a 'psychological barrier', triggered by both visual and olfactory clues, which pre-alert the animal to perceive danger ahead. In the wider landscape, promoting avoidance behaviour in elephants is what Guerbois et al. (2012) termed "using the ecology of fear".

Reliability of Data

Recorded reaction data were reliable, especially because elephants leave distinct footprints and other signs of their movements. Different behaviours like hesitancy, avoidance and aggression (damaging vegetation, tusking the ground) are relatively easy to detect retrospectively and can in turn be interpreted as individual animal behaviour by skilled trackers.

These reliably recorded reaction data mainly showing SVB avoidance in the study areas in Zimbabwe, directly correlate with equally reliable complaints by local farmers of elephant crop raiding incidents diminishing locally by up to 95%. There is no doubt that reports of success made by farmers in both Zimbabwe and Mozambique study sites, are genuine. Traditionally, smallholder farmers tend to exaggerate crop losses to elephants and other HWC species, so one can be quite sure that suddenly contrasting reports of successful release from this serious livelihood threat are reliable.

Effectiveness of a SVB

A crucial aspect of the new SVB strategy is that deterrence takes place both in natural habitat and some distance away from very palatable crops, thereby considerably reducing the strong temptation for problem elephants to continue forward to raid them. Elephants are naturally inquisitive animals and often spend time investigating strange objects or foreign smells. Being intelligent they are suspicious of 'foreign' visual items or olfactory stimuli like string or cloth saturated with pungent smelling chilli oil, or plastic bottles, reflective metal strips, cow bells or slow-burning chilli bricks, especially if these are unexpectedly encountered. In this study these flimsy items, not barriers in themselves but unexpectedly encountered upon their routes of habitual movement, merely acted as a bluff to elephants that people were actively trying to deter their progress, and so most chose to turn back or deviate substantially.

A surprising and extremely important finding in this study was that such repellence seemed not to depend so much upon the type of object (string, bottle, reflective tape, bell, smoke brazier) or the type of scent (chilli, creosote, old engine oil) deployed on the string, but upon the *strategic placement* of the foreign and scented object which aroused the elephants' suspicion and avoidance.

'Neophobia' – avoiding new objects like baits or traps, for example – is behaviour that has been described in literature for various animal species. A review by Greggor et al. (2015) mentions new objects, foods and unknown locations as triggers for animal neophobia, but does not mention scent. We are not sure if elephants' avoidance of our visual foreign objects can be ascribed to neophobia *per se*, or if the foreign olfactory stimuli are the primary deterrent. At this stage we believe it to be elephants using a combination of sight and smell, but as yet there is no real way to tell the proportional contribution of each. The fact that elephants show no fear of objects unadulterated with a foreign scent (e.g. plain fence wire, plain string, plastic bottles or reflectors), might suggest that a foreign scent is a much greater deterrent to them than a foreign object.

It was found unnecessary to physically link up individual short chilli string positions, since simply interrupting one principal approach path effectively promoted avoidance over a far wider *virtual* frontier. A spatially staggered deployment of scented strings as several 'layers' encountered before crop clusters, provided a longer boundary of very solid defence. So colloquially, this widespread avoidance by elephants could be ascribed to "putting the wind up them". At this stage we believe that situating a SVB inside the risk interface at 0.5 - 1km from crop cultivation boundaries, combines the best effect on elephants with easiest monitoring for people. If the risk interface is inside a protected area (PA), one may have to consider approaching the wildlife authorities and subject to their approval, deploying a SVB inside the PA.

An additional SVB benefit comes from the memory characteristics of elephants (Mumby and Plotnik 2018). Spatial memory characteristics displayed by animals (Burger-Tal et al., 2015; Barrett et al., 2019) strongly suggest the flexibility of the virtual fence dynamic may be able to withstand the chronic problem of elephant habituation to many traditional and static defence measures (Hoare, 2001b). And as further proof that the chilli string technique is remembered, in some cases avoidance of cropping areas (in Tsholotsho, Mbire) and municipal zones (Victoria Falls) persisted for appreciable intervals even if the SVB measures were not kept up. In the Mbire villages two reliable observations support this. When elephants passed through areas where SVBs had not been deployed for two years, they did not continue on to raid the local crops. In one case where some individual animals did start resuming passage into villages, redeployment of chilli string in the same previous sites stopped them again immediately (Collen Matema, unpublished data 2021).

Influence on Habitual Raiders

A behavioural observation noted in several HEC studies elsewhere, is that if the more dominant individuals who lead a crop raiding elephant bull group become reluctant to move forward for any reason, their subordinate companions appear to become similarly doubtful and do not persist on their own (Hoare, 2001a; Chiyo et al., 2011a; Chiyo et al., 2012). We believe this partly explains how a flimsy physical barrier causes 'cognitive' avoidance (Mumby and Plotnik, 2018; Barrett et al., 2019): being situated on pathways *only* in the risk interface, SVBs pre-alerted especially these boldest problem individuals to known danger far ahead, which they then decided to avoid. Thus the SVB technique likely has its own subtle 'multiplier effect' by deterring whole groups of elephant bulls. This ultimately reduces HEC to far lower levels than previous defences situated only at agricultural and village boundaries.

Across the study areas where physical characteristics differed, SVB success was most rapid when employed in conflict zones where elephants had been a relatively severe and long-term problem and there was already a history of human retaliation, especially control shooting in PAC. Lethal control in elephants is largely ineffective overall, because as 'habitual raiders' are individually removed, 'occasional raiders' gradually replace them (Hoare, 2001a; Chiyo 2011a). A decrease in elephants killed by official PAC in the Tsholotsho study area in Zimbabwe from 14 (an excessive number) in 2015 to none in the immediately following 2016 and 2017 seasons (Tsholotsho Rural District Council unpublished data; **Table 2**), dramatically illustrates a proxy of crop damage and personal threat to farmers.

Although elephants were the main target of our initiative, additional reports interestingly showed some evidence of apparent success against some other problem wildlife species. In Mbire District, Zimbabwe the chilli string monitoring data indicated some cases of avoidance by two lesser problem species using elephant paths - hippo (as crop raiders) and spotted hyaena (as livestock killers). And in Limpopo, Mozambique a simple chilli string experiment controlled the movements of crop raiding buffalo herds for a whole crop season.

Implications for Electric Fences

The pitfalls of trying to extend electric fence applications from well-resourced, well-managed and independent commercial agricultural business situations to large rural communities in under-resourced or poorly-managed subsistence agriculture, have now emerged after many years of monitoring (**Table 3**). In the latter, a raft of maintenance related issues (Hoare et al., 1998) frequently leads to failure.

Political pressures on conservation donors and foreign aid agencies frequently use the success of electric fencing in commercial agriculture to justify extending it to the subsistence agricultural sector. Even some ecologists have recently been encouraging greater use of conventional fencing to mitigate HWC in wild landscapes (Di Minin et al., 2021). Some elephant range states in Africa (Gabon and Kenya for example) have embarked upon national programmes of extensive and very costly electric fencing to try to mitigate HEC affecting subsistence agriculture (Osipova et al., 2018). We believe this approach, largely practiced by countries with centralized wildlife administrations, will suffer frequent project failure (**Table 3**) and is thus unlikely to be sustainable at a national level. We contend that a 30 year record shows both capital and recurrent expenditure for electric fencing on the scale required across vast areas of the subsistence agricultural sector in Africa can never be

TABLE 3 | Comparative summary of considerations for human-elephant conflict mitigation in agriculture with a soft virtual boundary versus electric fencing.

Conisdeartion	Soft virtual boundary insubsistence agriculture	Electric fence insubsistence agriculture	Electric fence incommercial agriculture
Ownership	Rural community	Rural community	Individual or Company
Capital cost	Low; no donor requirement	High; donor requirement	High but easily financed
Initial training requirement	Simple and cheap	Comprehensive, costly	Easily and quickly achievable
Knowledge required to implement	Local only	Imported and skilled components	Easily and quickly achievable
Physical layout in landscape	Flexible	Fixed	Fixed initially but can be changed
Routine maintenance of components	Simple, cheap, intermittent	Rigorous, continual – daily, costly	Rigorous, continual but easily achieved
Theft of components	No risk	High risk – common	Very low risk
Vandalism	No risk	High risk – common	Very low risk
Effect of vegetation overgrowth	Unaffected	Regular clearing needed, often neglected	Regular clearing needed, achievable
Elephant deterrence if not maintained	Extended effect	None – rapid failure	None, but failure far less likely
Sustainability	**Sustainable**	**Frequent project failure**	**Project failure very rare**

cost-effective. In poor management situations a SVB is far cheaper to install, requires far less maintenance, and suffers neither theft nor vandalism. So we propose that simple, low-tech, low cost and entirely locally applied measures like SVBs are a viable alternative for the current realities of HEC mitigation in rural community farming.

Overall Relevance to HEC Mitigation

The 'virtual fence dynamic' would seem to offer several enormous new advantages in HEC mitigation methods. Because the SVB methods (i) completely rely on local knowledge, (ii) were exceptionally low cost and (iii) demonstrated rapid results, the 'buy-in' from affected communities of poor subsistence farmers was immediate and extremely enthusiastic. This is something very seldom seen with other HEC mitigation methods and the SVB has been rapidly replicated by the word spreading in a growing number of the communal land farming areas of Zimbabwe and Mozambique.

The only implementation problems noticed in SVB trials were some farmers initially interpreting the idea as a physical fence rather than a virtual one, and some wrong placement too close to crop boundaries. These minor issues were easily addressed by facilitators engaged in our district council training programmes.

We encourage replication of the SVB technique elsewhere and suggest some experimentation with different visual and olfactory stimuli may be necessary in different elephant ranges. One recent study has claimed some success against crop raiding elephants using solar powered flashing (strobe) lights on crop boundaries (Adams et al., 2020). For the same set of reasons as explained above, we would suggest redeploying these lights to the risk interface to likely bolster a SVB with foreign scents. If affordable, we endorse the use of camera traps at the pathway interventions (Pozo et al., 2019) or radio collars on problem elephants to augment the collection of monitoring data. Collars are particularly useful to identify elephant movement corridors where HEC may be severe.

Therefore at the broadest scale the greatest advantage of the virtual fence dynamic is it has the potential to remove one of the most intractable stumbling blocks to the sustainability of HEC mitigation efforts in smallholder agriculture – reliance upon constant funding support from conservation donors. Making available a very cheap, easily self-applied and low maintenance deterrent is the most realistic way to boost self-reliance in HEC mitigation among smallholder agricultural communities potentially anywhere within the continental range of the African savanna elephant.

We propose SVBs could also be trialled where farm crop raiding occurs in the range of the African forest elephant (*Loxodonta cyclotis*), since they create and maintain distinct forest pathways upon which their nutrition and behavioural ecology become especially reliant. With smaller group sizes and usually a more placid demeanour being characteristics of forest elephants, blocking pathways to agriculture in the forest elephant range may prove somewhat easier than is the case in savannas.

Affected communities in our study areas are becoming much more supportive of non-lethal methods of dealing with problem elephants, having suffered endlessly from HEC despite decades of official control shooting. As a consequence of far greater self-reliance from using the simple SVB technique, rural communities and their often powerful political voices could thus potentially be 'weaned off' equally endless complaints that the primary responsibility for all HEC and all solutions to it, in any elephant range country in Africa, rests entirely with national wildlife authorities. If this attitude shift were to become widely accepted, official directives for lethal control could be much reduced, allowing most elephants still destroyed by wildlife authorities as a "ritual palliative" to rural communities (Hoare, 1995) to be saved. As a last resort to spare especially problematic and recalcitrant individual problem elephants from destruction, the newly experimental use of 'disruptive darting' (Langbauer et al., 2021) can also be attempted.

And finally and significantly by extension, if conservation donor agencies become increasingly released from political pressure to fund expensive and often unsustainable HEC mitigation measures like electric fences, monetary compensation schemes or translocating problem elephants, to protect relatively inefficient subsistence agriculture, donor initiatives could redirect their support towards a far better cause: the desperately-needed improvement of rudimentary crop farming methods perpetually being used in this sector.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This animal study was reviewed and approved by the African Wildlife Foundation.

AUTHOR CONTRIBUTIONS

MLG and RH share first authorship. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: Author MG is employed by African Wildlife Management & Conservation Ltd – which is simply given as his address. However, in this study he was acting in his private capacity as a wildlife management consultant.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.