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Impact of drought and development on the effectiveness of beehive fences as elephant deterrents over 9 years in Kenya

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Abstract

Human–elephant conflict is growing in Africa as human populations and development increases, creating disturbance to elephant habitats. Beehive fences have been trialed as a coexistence tool with some success but all studies have looked at small sample sizes over a short time period. Our study analyses the behavior of African elephants (*Loxodonta africana*) that approached a network of beehive fence protected farms in two conflict villages over 9 years next to Tsavo East National Park. We compare differences in elephant raids and beehive occupation rates annually, during a drought, and during peak crop production seasons. Out of 3999 elephants approaching our study farms 1007 elephants broke the beehive fence and entered the protected farm areas (25.18%). This was significantly less than the 2649 encounters where elephants remained either outside the farm boundary or broke into the control farms (66.24%). A further 343 elephants entered the farm by walking through a gap at the end of a fence (8.56%). The annual beehive fence break-through rates averaged 23.96% (±SE 3.15) resulting in a mean of 76.04% elephants deterred from beehive fences protected farm plots. Over six peak crop growing seasons the beehive fences kept between 78.3% and 86.3% of elephants out of the farms and crops. The beehive fences produced one ton of honey sold for $2250; however, a drought caused a 75% reduction in hive occupation rates and honey production for 3 years after negatively impacting honey profits and the effectiveness of the fences. Beehive fences are very effective at reducing up to 86.3%

of elephant crop-raids during peak crop seasons after good rainfall, but any increase in elephant habitat disturbance or the frequency and duration of droughts could reduce their effectiveness as a successful coexistence tool.

KEYWORDS

African elephants, beehive fence, crop-raid mitigation, human–elephant conflict, Kenya, participatory community trials, Tsavo National Park

1 | INTRODUCTION

Land-use change is one of the major drivers of biodiversity loss globally (Sala et al., 2000; Tittensor et al., 2014). As the global human population continues to surge, human expansion into wildlife habitats has risen and in the last six decades, almost a third of the global land area has been affected (Winkler et al., 2021). This has caused widespread fragmentation which is both physically destructive and can cause high levels of biodiversity loss (Haddad et al., 2015; Powers & Jetz, 2019). An increasing human population also increases the frequency of exposure of people to problematic natural entities, ranging from infectious agents originating in wildlife (Wilkinson et al., 2018) to much larger animals capable of significantly impacting income streams via their consumption of livestock or crops (Dickman, 2010).

Kenya is one fast-developing African country impacted by rapid land use change (Powers & Jetz, 2019). Kenya's human population increased by 59.4% between 2000 and 2020 (World Bank Population Statistics, 2022) and has brought expanding communities into ever closer contact with wildlife. Kenya also has one of the largest savannah elephant, *Loxodonta africana*, populations in Africa at approximately 36,260 (Waweru et al., 2021) and the densest elephant population in East Africa (Thouless et al., 2016). The country is experiencing an increase in human–elephant conflict (HEC) with the Tsavo Conservation Area experiencing an average of 836.4 recorded cases of HEC annually between 2017 and 2021—the worst impacted of any region in Kenya (National Human Wildlife Coexistence Strategy and Action Plans, 2024–2033).

There are a wide range of physical, acoustic, and olfactory deterrent methodologies which have been developed to facilitate the coexistence of humans and elephants while minimizing the negative ramifications of this cohabitation (Gross, 2019; King et al., 2023; Shaffer et al., 2019). This suite of options and tools of how to live with elephants ranges from simple night guarding (Massey, King, & Foufopoulos, 2014) to utilizing electric fences (Kioko et al., 2008), chili fences (Karidozo & Osborn, 2015; Osborn, 2002), wildlife trenches (Woodley, 1965), metal strip fences (von Hagen et al., 2021), watch towers (Gross et al., 2019), organic smelly repellent (Oniba & Robertson, 2019; Tiller et al., 2022), or noise and trip alarms (Gunaryadi et al., 2017). However, almost all these methods have both positive and negative case studies associated, with uptake and deterrent success varying widely across different environmental and socio-political conditions (Evans & Adams, 2016; Graham & Ochieng, 2008; Hoare, 2015).

Few methodologies offer an effective combination of being both a physical, olfactory, and acoustic barrier while also generating an income as the use of beehive fences (King et al., 2009, 2017) which utilizes the innate fear elephants show towards bees to repel them from areas of agricultural or other importance (King et al., 2007, 2010). The beehive fence has great theoretical appeal, providing farmers with alternative income streams in terms of honey and wax while repelling potential crop-raiding elephants, and supporting native honey bees at a time of global pollinator decline (Potts et al., 2010). The fences also provide a holistic solution to wildlife conflict and livelihood security that enhances both pollination and ecosystem services seemingly without detrimental effects on native bee species (King, Serem, & Russo, 2018).

Beehive fences are not without their management issues however, and they are reliant on healthy colonies of honeybees to provide the negative conditioning used to deter approaching elephants (King et al., 2010). Bees are highly susceptible to changes in climate and rainfall patterns with temperature increases reducing their range in the wild (Kimani, 2017) while variability in rainfall leads to changes in plant flowering periods and subsequent decreases in honey production (Akala et al., 2018). Water availability and associated impacts on flowering are the primary concerns to lowland beekeepers (Newman et al., 2021) and the global picture for pollinators looks bleak (van de Water et al., 2020) with the added concern that future climate scenarios are likely to benefit certain parasites of honey bees (Cornelissen et al., 2019).

Despite the complexities of beehive fence upkeep in the face of climate change, in many cases, beehive fences with strong bee colonies have been proven to be an effective and resilient method of mitigation against elephants in Kenya (King et al., 2009, 2017). In Tanzania, beehive fences successfully reduced crop losses to elephants for farming communities living with elephants outside of Udzungwa Mountains National Park, (Scheijen et al., 2019) and Kijereshi Game Reserve (Eustace et al., 2022). In southern Tanzania's Selous-Niassa wildlife corridor the majority of rangers also perceived beehive fences to be effective in mitigating conflict (Montero-Botey et al., 2021). In Mozambique, beehive fences prevented 95% of approaching elephants from entering farmland through previously well-used trails coming out of Gorongosa National Park (Branco et al., 2019); and next to Charara National Park 63% of 80 households previously impacted by elephants had no damage at all from elephants after erecting beehive fences with 100% of interviewees indicating that they would continue to use the beehive fence for the coming season (Virtanen et al., 2021).

Beehives can also be employed for wider usage than just the protection of farms with studies showing their efficacy at protecting trees from damage by both savannah elephants (Cook et al., 2018) and forest elephants *Loxodonta cyclotis* (Ngama et al., 2016).

Their effectiveness is not limited to African elephants, with evidence building of their suitability against Asian elephants *Elephus maximus*. In Thailand and Sri Lanka there have been signs of success (Butler, 2019; King et al., 2018; van de Water et al., 2020) and examples of small-scale usage of beehive fences also benefitting communities in Kerala, India (Nair & Jayson, 2016). Though a separate study into the behavior of captive elephants in Thailand found both European bees *Apis mellifera* and Indian bees *Apis cerana* to show little promise in stimulating retreat behavior even with well occupied hives (Dror et al., 2020).

The data from so many studies reveals that the statistics that classify "success" of beehive fences appears to be nuanced and variable depending on a range of environmental and social factors considered including which honeybee and elephant species are involved. This can lead to them being successful for some years or individuals but not for others (Virtanen et al., 2021), with the need for diligent maintenance playing a key role in this (Butler, 2019). A beehive fence project in Tanzania's Ngorongoro Conservation Area found in their study that they had no significant impact on crop raiding by elephants compared to chili fences, but the small sample size ($n = 2$ farms) and low bee occupancy was a hypothesized contributor to this result (Kiffner et al., 2021). Bee activity is clearly key to their deterrent effectiveness as unoccupied or sedentary hives have been shown to be ineffective at repelling elephants (Ngama et al., 2016; Scheijen et al., 2019). Low bee activity can be exacerbated by pests and parasites particularly ants which pose a frequent irritant to successful colonies (Thornley et al., 2023). Additionally, excessive use of pesticides sprayed on crops near beehive fences can exacerbate colony poisoning and loss of individuals and may subdue the capabilities of the honey bees to deter elephants, as well as reduce motivation for fence maintenance (Butler, 2019).

Here, we present the longest known study conducted by Save the Elephants on the efficacy of beehive fences in deterring African savannah elephants from crop raiding. By analyzing a 9-year dataset from nearly 4000 encounters with elephants within the Tsavo Conservation Area we hope to provide a thorough understanding of the varied, long-term impacts of beehive fence usage on crop-raiding by elephants in a semi-arid environment with the aim of providing evidence for the inclusion of the method for other conflict hotspots in the elephant range.

2 | MATERIALS AND METHODS

2.1 | Study area and farm selection

Kenya's vast Tsavo Conservation Area encompasses 42,000 km^2 and is comprised of a mixture of community ranch lands, semi-arid bushland, and acacia-savanna forest. Before the ivory onslaught of the 1980's Tsavo was once home to 35,000 elephants (Douglas-Hamilton, 1989) and although numbers have plummeted it still hosts Kenya's largest elephant population. At the start of our study in 2012 there were 12,573 individuals (Ngene et al., 2013) which had grown by the end of our study in 2020 to 14,964 elephants (Waweru et al., 2021). Two seasons of rainfall occur within Tsavo with long rains occurring between March and May, and short rains between October and December with patterns of annual rainfall being notoriously unpredictable, ranging from 250 to 700 mm, with a long term average of 550 mm (Ngene et al., 2017).

Taita Taveta County is surrounded on three sides by Tsavo National Park and is home to around 340,000 people encompassing human settlements, small-scale farming, private ranches, and conservancies. The county acts as a vital corridor and dispersal area for wildlife migrating between Tsavo East and Tsavo West National Parks (Smith & Kasiki, 2000). The communities living in these ranches are typically low income with only 21.9% of individuals finishing secondary school and only 15% of households having electricity (2019 Kenya census). Alongside a 50% unemployment rate, nomadic pastoralism, livestock, and small-scale farming provide critical livelihood support and income (2019 Kenya census). Lower Sagalla is one such rural Taita farming community that consists of four neighboring villages that lie at the eastern base of Sagalla Hill, only 3 km from the boundary of Tsavo East National Park. Elephants have historically migrated in and out of the unfenced park boundary causing clashes with the Sagalla communities as they disperse around Taita-Taveta county (King et al., 2017).

Two villages within Sagalla, Mwakoma and Mwambiti, were selected for the study and have a combined population of approximately 1,300 residents living in 340 households. During multiple participatory meetings, 110 farms were identified and mapped as front-line high-conflict sites where elephants reportedly broke into farms to feed on growing crops: typically maize, beans, watermelon, and pumpkins. Almost a quarter of this subset of 110 conflict farms, 26 farms in total, were chosen through participatory community meetings where the most impacted and most vulnerable farmers were actively selected by the community members to receive a trial beehive fence (refer to King et al., 2017 and Map in Figure S1, Supporting Information).

2.2 | Construction of beehive fences

We constructed beehive fences throughout the 9-year study period, starting in 2012 with 8 beehive fence-protected farms comprising 115 beehives (as described in King et al., 2017) and culminating with a peak of 26 beehive fence protected farms comprised of 365 beehives by 2019 as demand grew from within the communities (King et al., 2017). At the end of 2019 three of the beehive fences were taken down as two farmers died, and one was too sick to participate in the study leaving 23 farms protected by beehive fences and 325 beehives in the study for 2020 (Figure 1). Additionally, in 2018 two beehive fences and their occupied hives were moved when the two farmers left the community. The study and data collection from those two sets of beehives continued without a break on the new farm sites less than 300 m from the previous farm location so were included in the analysis as an unbroken dataset.

Each beehive fence was constructed in accordance to the detailed design outlined in King et al. (2017, 2009). Each farm had a set of between 12 and 15 beehives, each hung between two 2.4 m posts spaced 3 m apart. The next set of posts were positioned 7 m away and either a beehive or a dummy (i.e., imitation) beehive was hung every 10 m apart, interlinked by 12 gauge/2.64 mm plain fencing wire. Four farms in the original eight beehive fences built in 2012 were constructed with Kenyan Top Bar (KTB) Hives made out of plywood but the remaining 22 beehive fences were all constructed with interlinked Langstroth and dummy beehives (Figure 2). The KTB hives and Langstroth hives cost US$35 and US$60 each, respectively. Farms with 12 hives and 12 dummy's cost us $550 to install with KTB beehives, or $850 to install with Langstroth hives including costs for dummy hives and wire (King et al., 2017). Usually, *Commiphora* spp. posts (a genus of trees that include the frankincense and myrrh families) were coppiced for free from the surrounding bush which have the advantage of cut trunks re-growing once embedded into the soil. If posts had to be purchased (as was the case for one or two farms without enough *Commiphora* spp. nearby) the posts cost approximately $3–4 each (48 posts = approximately $192). The Save the Elephants charity donated the beehives and wire to each of these study farmers experiencing high elephant conflict, while the recipient family donated the posts and labor for construction.

The four fences comprising KTB beehives were all replaced by stronger Langstroth hives from 2016 onwards as the plywood began to weaken. Data from the first initial 10 beehive fence farms built in 2012/13 were described in King et al. (2017) and have been included here for this larger data analysis.

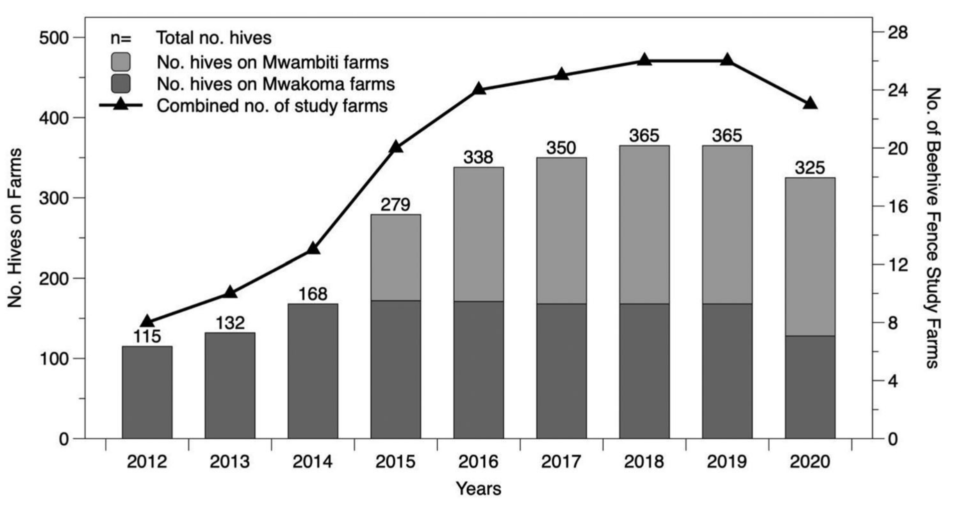

FIGURE 1 Overview of number of beehive fence farms and total number of hives in beehive fence farms within each of two villages in Sagalla community over the 9-year study period.

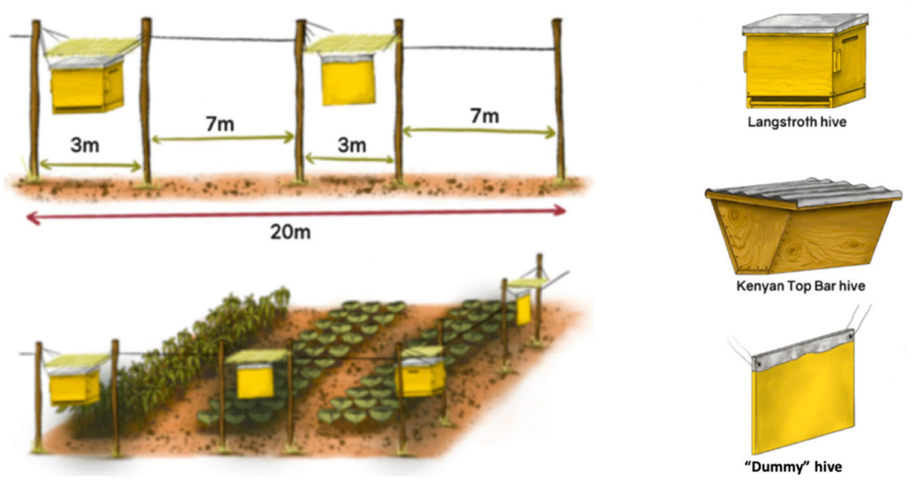

FIGURE 2 Design of beehive fence around the perimeter of each farm using either KTB ($n = 4$) or Langstroth hives ($n = 22$) and alternating beehive with a dummy hive every 10 m. The hives are connected with plain fencing wire that, if shaken by intruding elephants, helps to swing and disturb the interlinked hives and release the bees. Previous studies have shown that even just the sound of bees alone is enough to make elephants run away (King et al., 2007).

Each farm had between 1 and 1.5 acres of crop land protected with the beehive fence with an equivalent size of farm set aside as a control plot adjacent to one side within the same farm area. Every farm already had in place a simple thorn fence barrier around them as was customary in Sagalla community. These had been installed to try to deter elephants and other wildlife species such as baboons. While the layout of each farm was unique, we built the beehive fence around the portion of the farm in the most vulnerable location to elephants with the same size control portion of the farm usually adjacent or to one side of the property. This "real world" design had the benefit of deliberately biasing the trial to test the beehive fence design in the most intense conflict spot where elephants most regularly entered the study farms to crop-raid and the control portion of the farm tended to be the second most impacted area of the farm. The fences were mostly rectangular or circular when installed, sometimes with a small gap of around 10–40 m left on the side nearest to the house to avoid having live beehives sitting too near the farmers' living quarters. Swarms were left to colonize hives naturally, but attractants such as wax and lemongrass oil were added to speed up occupation rates.

In response to elephants getting through into the protected plots through these small end gaps in the beehive fence near to the farmers' homes, in very late 2018/early 2019 we added additional short stretches of "tin-cans-and-stones noisemakers" to close off these gaps in the beehive fences. This traditional method had been observed to work elsewhere (Gunaryadi et al., 2017; Sugiyo et al., 2016) and consists of tin cans strung on wire between trees and fence posts with stones placed inside. If an elephant tries to push through this barrier the stones rattle inside the tins and either the noise would dissuade the elephants from continuing to enter the farm, or they wake the farmer up who can then have the chance to chase the elephants away from entering the farm.

2.3 | Monitoring farm events

This annual growth in beehive fences was driven by demand for the fences from the two communities of Mwakoma and Mwambiti (King et al., 2017) and we matched this demand with monitoring capacity to ensure data collection was conducted regularly across all farms. Farms were visited frequently, at least twice per month, to check the participating farmer's data sheets to ensure the dates of all new hive occupations and bee colony absconding cases were recorded accurately. Additionally, every elephant crop-raid at every study farm was visited the day after the event to help the farmer capture all the information as accurately as possible on the behavior of elephants around the beehive fence study farms.

Farmers helped record data on any elephant movements and these were classified into six categories and included the number of elephants that: (a) were in the event, (b) avoided the farm altogether, (c) entered the control farm area, or (d) broke the beehive fence to enter the protected farm area. Additionally, we recorded any elephants that (e) walked along the fence and entered the fence through an unprotected gap, or (f) who broke the beehive fence and immediately retreated without entering the farm, presumably deterred by the act of the break or the swarming of bees from the disturbance of the beehive.

The number of elephants in each event was estimated by first talking to the farmer and verifying their experience of the event. Then we checked this information by tracking and counting any elephant footprints or urine/

dung signs within 30 m around the outside of their farm, or that had entered inside the farm to verify that the sex and perceived number of elephants was accurate. In events when dozens of elephants were encountered, a best guess estimate was recorded after both verbal and practical assessments were complete. This checking of footprint data was very important as perceptions of the number of elephants was occasionally greater than what was later accounted for in careful analysis of the footprints.

To assist us with counting elephants in each crop-raid we installed between 12 and 20 camera traps on the most raided farms across the years to help capture head shots, sex, and number of individuals as elephants moved around the villages. These images were regularly cross checked with the nearest beehive fence when there was a conflict event to help verify farmer reports and best-guess estimates of the number of elephants in each crop-raid.

We classified an encounter of a group of elephants at each farm as an "elephant event" with every elephant in each event counted as the "number of elephants in events." The total number of elephants in events in our analysis is therefore not representative of a total number of individual elephants, rather the total number of elephant interactions experienced by the community as independent conflict events. That is, one bull could visit six farms in a night and although it was the same individual bull, six elephant events would be recorded in the dataset, one logged from each site. We classified an event as soon as an elephant was within 30 m (or less) of a study farm. We counted what each elephant did in each event as the independent data variable rather than classifying what each group event did. This was because we often had groups where only one elephant broke or breached a beehive fence and the others did not follow. Hence, recording a classification of a group breaking or not breaking a beehive fence was too simplistic and one that would have lost nuance in the gradation of potential negative impact for the farmer.

Bi-monthly data collected on hive occupations from each beehive in the study enabled us to record presence/absence of honeybees, any pests or parasites affecting the hives, the number of bars of honey ready for harvesting, and the total volume of raw honey produced from each hive. This weighed raw honey was processed into pure honey, poured into jars and sold. The farmers were paid per bar of raw honey that was extracted from their beehive fences and this productivity data was used as an indicator of colony strength and as an indicator of the level of livelihood benefits derived from the project each year.

Rainfall was collected daily in a rain gauge based at the Elephants and Bees Research Centre in Mwakoma Village from January 2014 until December 2020. For 2012 and 2013, before our research center was built, we used rainfall data from the Voi town meteorological office stationed 5 km away.

2.4 | Significant landscape events

Five important landscape events occurred during this 9-year study period (Table 1) that likely influenced the field conditions during the trial and are discussed in the results.

2.5 | Data analysis

All data were analyzed using Data Graph v.4.7.1, Excel v.16.15 and Minitab Express v.1.4. Due to the organic growth of the network of beehive fences over the 9 years, we analyzed the data using linear regressions, Pearson's correlations, and proportions to show each year as a percentage of the overall data collected. This helped to standardize the data as much as possible across years despite the steady increase in the number of beehives over the course of the study. We only analyzed farm raid data for this study, excluding any encounters that occurred at farmer houses (i.e., events where elephants broke into houses, or water tanks were excluded from the analysis).

The data were analyzed in two formats. First, we compared 9 years of data from each calendar year (January–December) to analyze all elephant numbers in all crop-raid events, all hive occupations and annual rainfall. The only exception was our first year in 2012 from which we could only analyze data from June to December as the first eight beehive fences were only finished in June 2012.

Second, we analyzed events during the main 3-month crop growing seasons that occurred each year during the short rains which fell between November and January and straddled calendar years. For this subset of crop-raid data we looked at six crop seasons, this incorporated 2 years of average rain before the big drought (2014/15 and 2015/16) then the two seasons of very poor rains that were classified as a drought (2016/17 and 2017/18) followed by two further years of average rainfall (2018/19 and 2019/20). Differences between elephant fence breaks and events where the fence deterred elephants for each farm were compared using paired t tests.

3 | RESULTS

Between June 2012 and December 2020, we recorded a total of 675 distinct human–elephant conflict crop-raid events in and around the study beehive fence protected

TABLE 1 Five important landscape events occurred during this 9-year study period and their impact on elements of the study.

Event	Date	General impact on environment	Impact of event on beehive fence farms
Standard gauge railway construction	Started early 2014; barrier fences complete and trains start in 2017	Although underpasses for wildlife were created during the SGR construction, they took time to be constructed and it took elephants and other wildlife time to figure out the crossing points. Some elephants remained inside communities as they tried to find access points back to the park	Good annual rains meant hive occupancy remained high, beehive fences deterred the majority of the increasing number of elephants and produced 812 kg of honey in the process
Drought	The November 2016 rains fail and this is the start of the 18 month drought	Just 288.1 mm of rain fell in 2017 compared to the average of 691.2 mm from the other 8 years	Occupation of hives plummeted from 60% to 7.7% between late 2016 and late 2017
Mass illegal grazing	Good rains return in October–December 2018	Cattle invasion into national parks for grazing. Efforts by KWS to push cattle out of parks potentially pushed elephants into communities. 1,833 elephant encounters were consequently recorded around the study farms between Nov 2018 and Jan 2019, with one farm reporting that "100 elephants broke inside the beehive fence"	Lowest success rate for beehive fences, with good crop yields from rains enticing large herds of elephants into farms with fences stopping just 71.8% of elephants during this season
Unpalatable crop project commences	2019	129 farmers started growing sunflowers which elephants are highly unlikely to eat	This may have made farms less attractive to elephants as we saw crop-raid events reduce
COVID-19 lockdown	2020: lock down begins in Kenya in late March 2020	Recording crop-raiding events became more complex and the in-person interviews following events were no longer allowed. The lockdown curfews stopped tourism and reduced livestock disturbances to elephants inside the parks	Interviews were replaced with phone calls. The lower disturbance level possibly influenced the reduced number of elephants leaving the parks to enter the Sagalla community in 2020

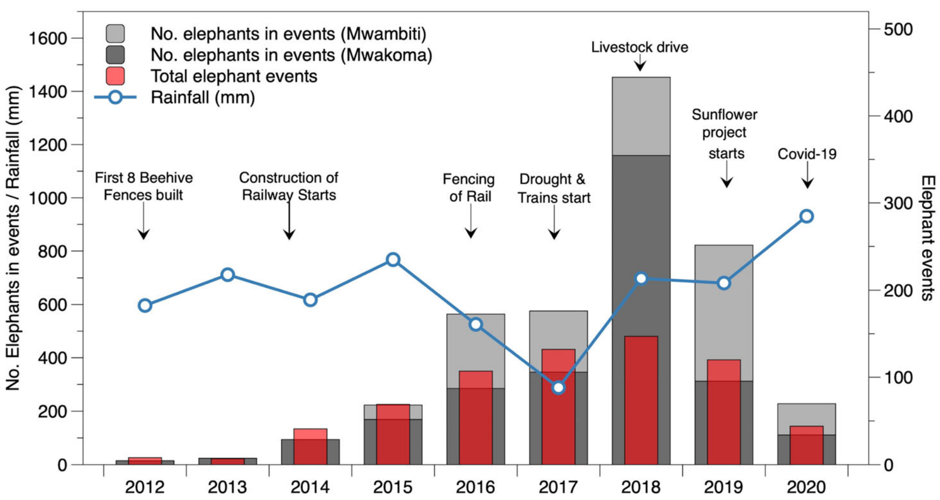

FIGURE 3 Elephant events in Sagalla and number of elephants in events in each village of Mwambiti and Mwakoma rose and fell over the study period. Annual rainfall variations and significant external activities that may have influenced the number of elephants arriving in the community each year are indicated.

farms that involved unsuccessful or successful attempts at accessing the crops. There were 3999 elephant encounters with the beehive fence farms in those 675 events (Figure 3). Some of these encounters involved multiple farm raids, or visits, across several study farms in one night.

Elephant crop-raid events in both villages in Sagalla increased annually from 2012 ($n = 8$; one event per study farm per year across eight farms) until a peak was reached in 2018 ($n = 147$; an average of 4 events per study farm per year across 26 farms). Elephant crop-raid events started to decline in 2019 ($n = 120$) and 2020

($n = 44$) with Mwambiti over taking Mwakoma with the greatest proportion of elephant events recorded (Figure 3). Likewise, the number of elephants and the group size of those elephants in each event increased over the years with a peak mean group size rising from 1.8 (±SE 0.23) in 2012 to 9.88 (±SE 1.58) in 2018. The larger the number of elephants that came into the community each year, the greater the group size (Linear regression $R^2 = 0.8867$, df 8, $p = 0.022$; Figure 4).

Invasions of elephants into the farms peaked in 2018 with 1064 elephant encounters recorded in the 147 events either entering inside the control areas, or seen immediately around the outer boundary, of the 26 study farms (Figure 5). The worst years for breakages of beehive

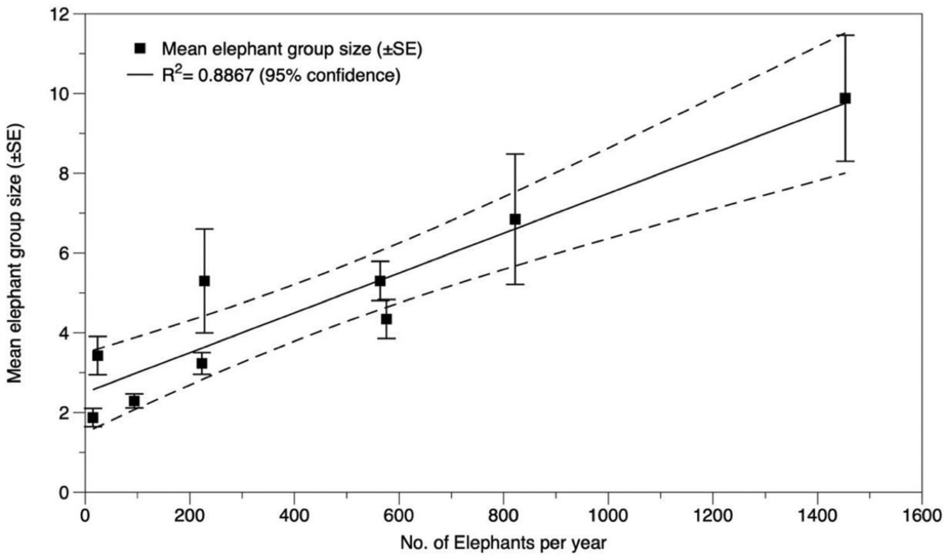

FIGURE 4 Positive correlation between the number of elephants entering the farms annually and the recorded mean elephant group size (Linear regression fit $R^2 = 0.887$, df 8, $p = 0.022$).

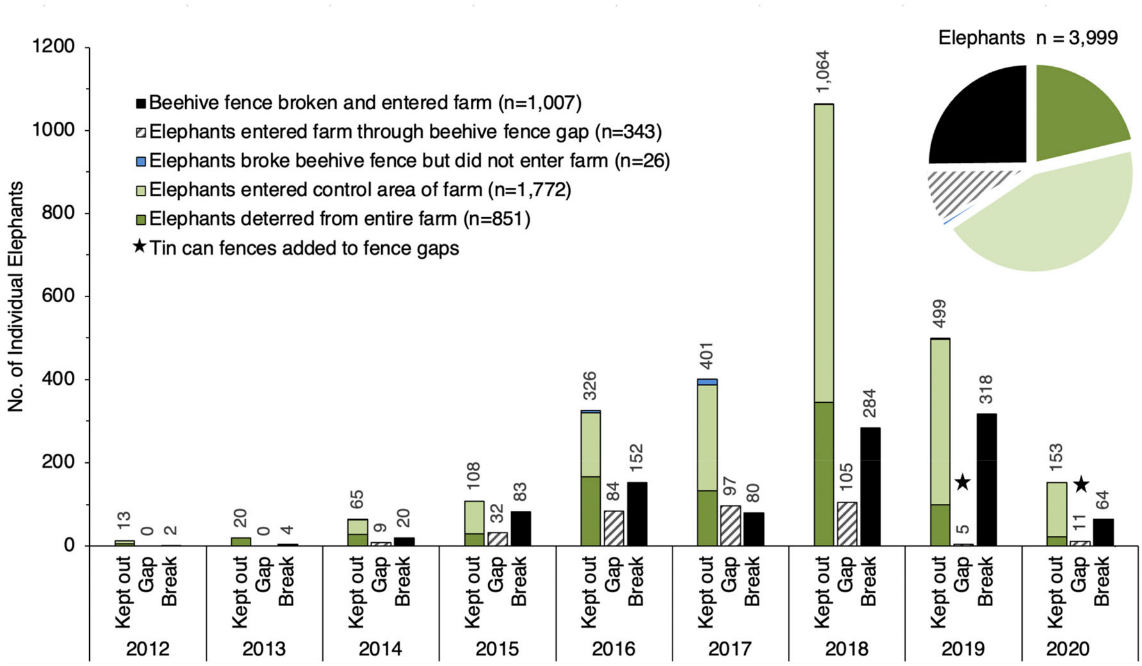

FIGURE 5 Out of 3999 elephants approaching our study farms 1007 elephants (25.18%) broke the beehive fence (black) and entered the protected farm areas. This was significantly less than the 2649 encounters (66.24%) where elephants remained either outside the farm boundary (dark green) or broke into the control farms (light green). A further 343 elephants (8.56%) entered the farm by walking through a gap at the end of a fence (dashed grey). Twenty-six elephants broke the fence but still did not enter (blue). Elephants entering the farms through any small gaps reduced in 2019 by the addition of small stretches of hanging tin cans with stones inside (star) to the fences that closed off the gaps and additionally helped alert the farmers to the presence of elephants attempting to enter the farm.

fences were 2018 and 2019 with 284 (19.6%) in 2018 and 318 (38.7%) in 2019 of elephants managing to break into the farms through the 26 beehive fences. The 2019 data included an unverified anomaly of "100 elephants" recorded by one convinced farmer on one rainy January night inside a beehive fence that we were unable to verify due to rain obscuring the footprints. We were unable to disprove his report, so although this was classified as an outlier the event remained in the analysis (Figure 5).

During the 9-year study period, a total of 2649 encounters where elephants approached the study farms saw them either stay outside the farm boundary completely or crop raid inside the control farms. This was significantly more than the 1007 elephants that broke into the beehive fence areas of the farm over each of the 9 years (two-sided paired *t*-test $t = 2.505$, df $= 8$, $p = 0.037$). Additionally, 343 elephants managed to get into the beehive fence area through a gap in the beehive fence structure (i.e., not breaking the fence but taking advantage of the beehive fences on some properties not completely surrounding the farm). The addition of inter-linked tin can and stone fences to seal any gaps in the end of the beehive fences at the very end of 2018/early 2019 helped to reduce the number of elephants that broke in through a gap in the beehive fences for the 2 years afterwards from 343 in the previous 5 years (2014–2018) to just $n = 5$ in 2019 and $n = 11$ in 2020 (Figure 5).

The proportion of elephants that broke through the beehive fences in all recorded events varied each calendar year from lows of 13.33% in 2012 (project start) and 13.89% in 2017 (drought—no crops in farms) to a high of 38.69% in 2019 the year which included the anomaly event from the Farmer of "100 elephants." The average proportion of elephants that broke the beehive fence each calendar year was 23.96% (±SE 3.15) meaning that over the long term one could plan for a beehive fence protected farm to repel 76.04% of elephants (Figure 6).

Hive occupation peaked in 2015 with 86.74% (242 hives) of the 279 beehives placed out on the farms being occupied by honeybees at least once during the year. The lowest annual occupation rate was seen during the drought year of 2017 with only 20.29% (71 hives) of the 350 beehives being occupied by bees at least once during the year. The annual average occupation rate for the beehives across all farms and all 9 years was 52.1% (±SE 7.21) (Figure 7a). Higher annual rainfall rates led to an increase in annual hive occupation rates across the 9 years of the study but this direct relationship was not statistically significant (Linear regression $R^2 = 0.317$, df 8, $p = 0.114$) (Figure 7b).

There were 628 bars and 812.37 kg of honey produced by 338 beehives in the beehive fences in the 3 years prior to the 2017 drought (2014–16). No honey was harvested during the drought of 2017. During the 3 years after the drought, only 142 bars and 187.68 kg of honey were produced from 365 hives (2018–20). In total 770 bars and 1000.1 kg of raw honey was produced from the beehive fences across all 9 years of the study (2012–20) generating approximately US$2250 as an income for the 26 farmers. In addition, 20 different types of hive pests and parasites were recorded in and around the beehives over the years with the top 8 most common pests being wasps, ants, lizards, cockroaches, spiders, beetles, grasshoppers, and wax moths. Due to inconsistencies in data collection for measuring pest numbers, we were not able to assess accurately if pests and parasites increased or decreased after the drought.

Out of the 3999 interactions where elephants approached the study farms across the 9 years, 76.19% of

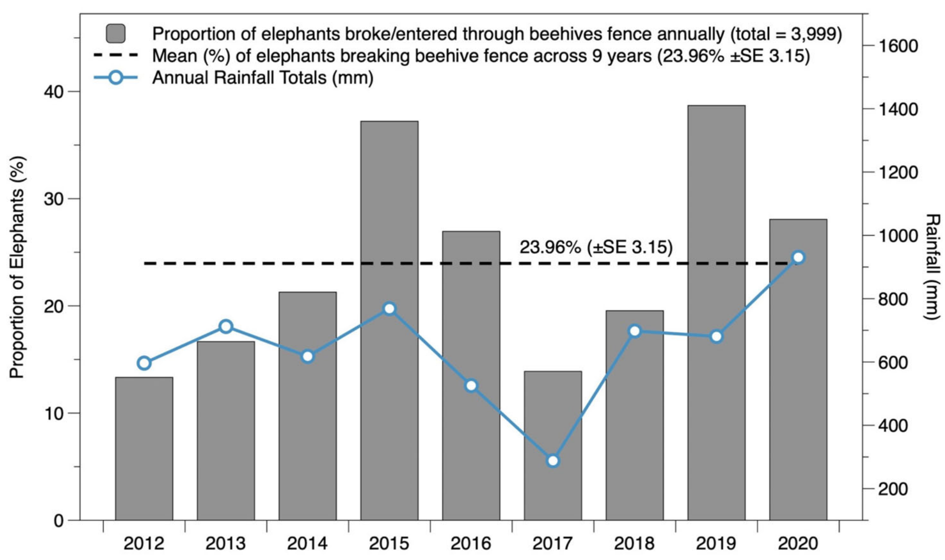

FIGURE 6 Proportion of elephants breaking the beehive fences or crossing through (once broken) to enter the protected portion of each farm revealed an annual average of 23.96 (±SE 3.15) elephants that succeeded in getting through the fences across the 9 years.

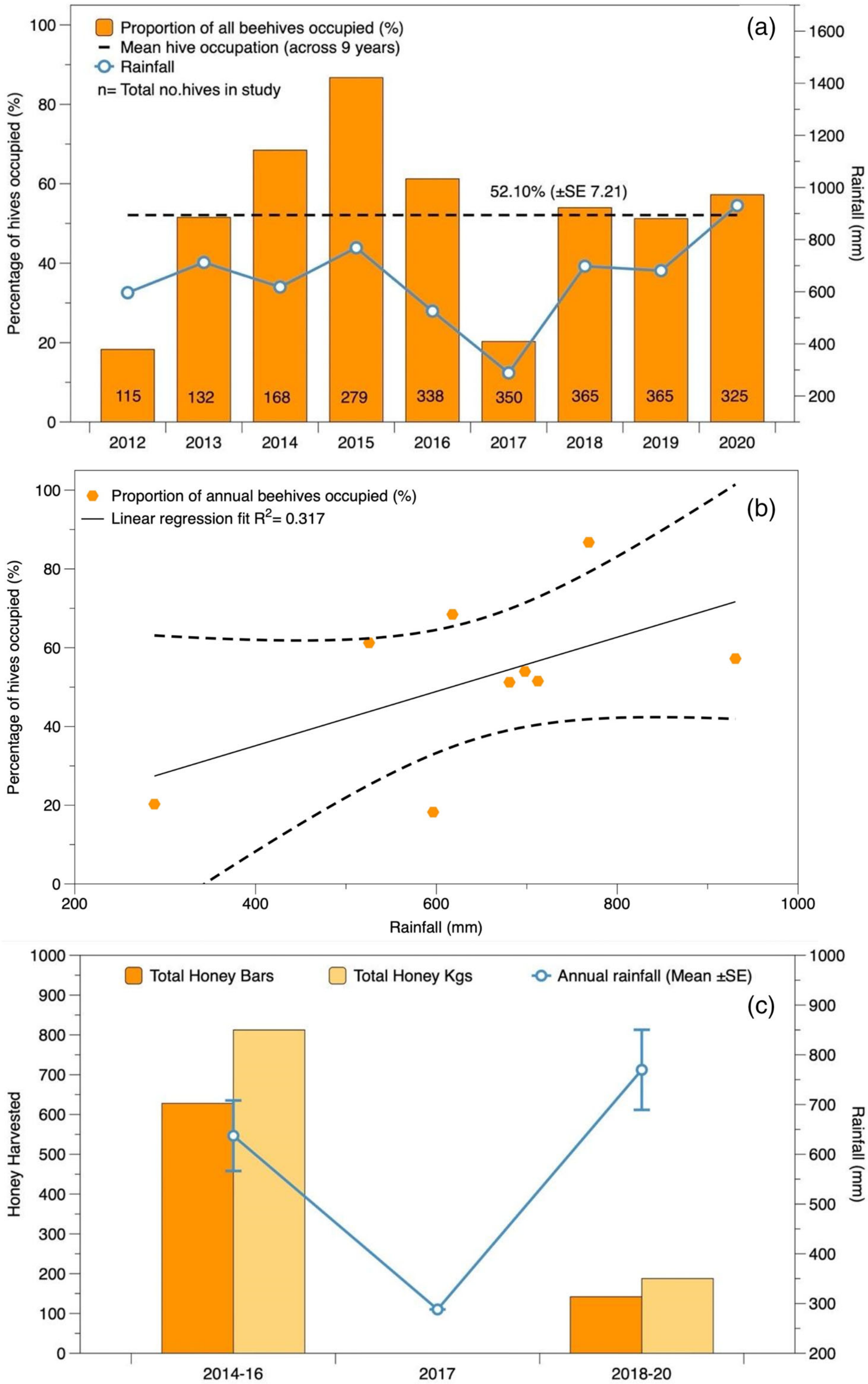

FIGURE 7 (a) The proportion of beehives that were occupied at least once during each year of the study compared to annual rainfall highlighting the impact the 2017 drought had on hive occupations. (b) Annual rainfall was positively correlated to annual hive occupation rates but was not statistically significant (Linear regression fit $R^2 = 0.317$; df 8; $p = 0.114$). (c) The 2017 drought had the impact of drastically reducing production of both bars and quantity of honey to less than a quarter of pre-drought volumes.

the elephants ($n = 3047$) approached the farms between November and January each year which was over the short intense rains and was therefore the major crop growing season each year. As this was the time when the farmers most needed crop protection, the data for six of these major crop growing seasons were analyzed separately from November to January 2014/15 onwards until November to January 2019/20 which involved 3027 elephants across the six crop growing seasons (75.69% of all events recorded).

The percentage of elephants that broke the beehive fences varied during each of these six peak crop seasons from 0% breaks (2014/15) to the worst year for beehive fence breakages being 2018 when 28.4% of elephants that

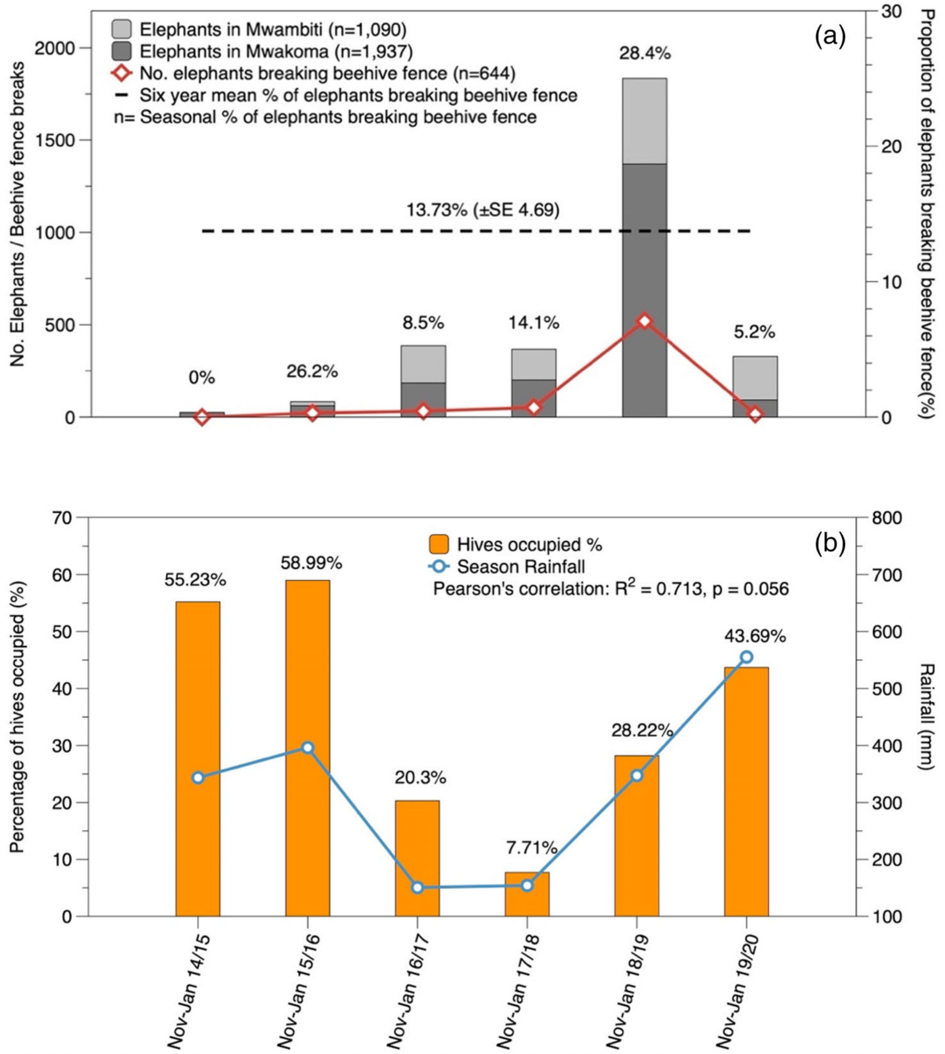

FIGURE 8 (a) The proportion of elephants in each crop-raid season that broke the beehive fences varied each year with a peak of 28.4% observed during the season when 1833 elephant encounters were recorded in the community between November and January 2018/19. The mean of these high season breaks of the beehive fence was 13.73% (±SE 4.69) across the six crop-raid seasons. (b) Occupied hives during peak crop-raid seasons were positively correlated to rainfall (Pearson's one-tailed correlation $R^2 = 0.713$, $p = 0.056$).

approached farms broke the beehive fence (Figure 8a). A total of 644 out of 3027 elephants broke through the beehive fences across all six peak crop seasons (21.28%) meaning that 78.78% of elephants were kept out of beehive fence protected farms during the peak crop seasons. To account for all the different conditions occurring throughout the community each crop-season, the mean beehive fence breakthrough rate across the 6 years of peak crop seasons was 13.73% with a mean beehive fence elephant deterrent rate of 86.27%.

Hive occupation rates closely mirrored rainfall volumes during these six peak crop-raiding seasons with an increase in seasonal hive occupations positively correlated to an increase in seasonal rainfall (Pearson's one-tailed correlation $R^2 = 0.713$, $p = 0.056$). Hive occupation drastically reduced in the 2016/17 and 2017/18 crop seasons in response to the poor rainfall that led to the bad drought the community experienced during the whole of the 2017 calendar year (Figure 8b).

4 | DISCUSSION

Our study into the effectiveness of beehive fences as elephant deterrents for small-scale farms in rural Kenya spanned 9 years, over which we achieved an annual mean rate of deterring 76.02% of elephants from farms across the study period and 86.27% of elephants during the peak crop seasons. Over the course of the study five external landscape and environmental changes were likely contributors that influenced the variation in the number of elephant events recorded within the two study communities which consequently tested the long-term effectiveness of beehive fences as elephant deterrents under varied conditions (Table 1).

It is possible that the construction and fencing of the Standard Gauge Railway reduced the free flow of movement for elephants from Taita-Taveta trying to re-enter Tsavo East National Park (Okita-Ouma et al., 2021) and created an increase in elephant events inside the villages in Sagalla from 2014 to 2016. However, whatever caused this increase in elephants the good annual rains meant the hive occupation rate remained high during those earlier study years and the beehive fences were able to deter the majority of elephants from entering the study farms. The farmers also harvested over 812 kg of honey which provided double motivation for good fence maintenance.

Droughts are well documented to have negative impacts on pollinators (Descamps et al., 2021), and during our study a drought began in late 2016 with a failed end of year rainy season. This yielded just 288 mm of rain throughout 2017, 42% of the average rainfall experienced over the other 8 years of the study (mean 691 mm ± SD 122.9). As a result, the occupation of the 350 hives in the beehive fences plummeted from over 60% to just 7.7% during the November–January 2017/18 season. Despite the low hive occupation rates that season, the number of beehive fence breakages by elephants remained low with 86.27% of approaching elephants effectively deterred. However, with such poor rains, the growth of crops was limited, and consequently farms were likely to have appealed less to elephants reducing the incentive to break through the beehive fence barriers. An important consideration of beehive fence implementation is that as climate change progresses and droughts worsen, they may become a less versatile solution to HEC as the number of bee colonies in our study hives were shown to be negatively impacted by low rainfall.

Between November and January 2018/19 we had 1833 elephant encounters around the 26 study farms which occurred after high rainfall in late 2018, a time when Kenya Wildlife Service increased efforts to drive illegal cattle grazers out of the neighboring parks. When under stress or in response to human disturbance, both savannah and forest elephants have been observed bunching together in larger herds for protection (Meier et al., 2023; Shannon et al., 2013) and the disturbance from the cattle drives inside the parks might have caused these large group sizes to form and enter the community farmlands in 2018 and 2019. The high rainfall had also helped increase hive occupation from a low of 7.7% from the preceding drought year to 28.2%. However, with over two thirds of all hives still unoccupied by bees the beehive fences saw their greatest beehive fence break rate during this peak elephant conflict season at 28.4% of elephants managing to break the fences and access the farms. This was the "perfect storm" of low hive occupation with weak bees recovering from the drought, and an unprecedented invasion of elephants coming in large group sizes into the farms that had much larger and healthier crop yields due to the good rains (Figure 4). This combination of events resulted in the beehive fences only stopping 71.8% of elephants during this season, the lowest deterrent rate recorded over the six peak crop seasons.

Despite the lower deterrent rate during the November–January 2018/19 season, the mean deterrent rates of the beehive fences over the six peak crop seasons was 86.27% of elephants. This meant that when comparing averages from each unique season, a mean of 13.73% of elephants managed to break into the farms across the 6 years of peak crop growing when the farms most needed protection from elephants as their crops grew. This figure is a "mean of means" which we have justified as a summary due to both the variation in the number of beehives in the study (Figure 1) and the variation in climate and field conditions each year (Figure 3).

This mean of means figure of 86.27% describes the most likely elephant deterrent rate over a long (9 years) time period for how effective beehive fences are on average during peak crop-raid seasons. This is greater than previous recorded deterrent rates of 80% from our previous analysis of a shorter-term, smaller subset of 10 farms (King et al., 2017) and goes to show the value of long term, large scale studies for testing new elephant mitigation methods over multiple crop seasons, particularly when such studies are reliant on rain-fed agricultural activities where drought and other extreme changes in landscape and land use issues can swing field conditions dramatically from one year to the next.

In this analysis we did not compare daily crop-raids with daily hive occupations as our previous study had already shown that low hive occupations lead to higher breakages of beehive fences (see King et al., 2017). Our analysis was focused on the bigger picture of how effective beehive fences can be across multiple years and varied conditions which ultimately is the most important result for whether communities and project managers should consider implementing beehive fences as helpful elephant deterrents in the future. With such a high mean seasonal deterrent rate of 86.27%, there is no doubt that beehive fences should be included in the toolbox of options for small scale farmers to help reduce human–elephant conflict in the future. However, before implementing a beehive fence project, communities should be aware of the design recommendations and set-up costs of this deterrent plus the maintenance commitments required for beehive fences to remain a successful deterrent. For our project working with small scale, individually protected farms, the breach of one fence only led to crop raiding within just one farm. Using long stretches of fence to protect multiple farms seems an alternative design option but it means the ramifications of one breach can be felt throughout an entire community with elephants able to then disperse throughout multiple farms following just one break.

In our study we decided not to measure the actual extent of damage of the crops if any elephants broke into the control or beehive fence protected portion of the farms. Any incursion by elephants is clearly important to the farmer but accurate crop-damage measurements are rife with challenges and reality often differs with perception (Kiffner et al., 2021). Crop assessments are also extremely time consuming, and damage varies between growth status of each plant which can vary both within and between farms making wildlife crop-damage estimates often inaccurate. Additionally, they can come layered with tricky social pressures for evaluators related to compensation claims. We decided to focus solely on whether our barrier design worked to reduce elephant incursions and made the assumption that any incursion was a negative experience for the farmer whether crops were damaged or not.

One impact of the drought we experienced was that the bee colonies did not recover quickly and hives remained with low occupation rates (28.2%) for another year which had the knock-on effect of making the beehive fences less effective at deterring elephants when the farmers experienced 1833 elephant encounters in the community a season later in November–January 2018/19. The 3 years after the drought also saw disappointingly low honey production for the farmers, with only 187.68 kg of honey produced compared to pre-drought volumes of 812.37 kg over the same window of time despite an increased number of hives (Figures 1 and 7c). The importance of occupancy and healthy bee activity to the success of a beehive fence as an elephant deterrent cannot be overstated, not only for occupancy and its associated elephant repellence but also for honey production and for the financial and pollination benefits of the hives to be reaped by farmers (Denninger Snyder & Rentsch, 2020; Dror et al., 2020; Ngama et al., 2016; Virtanen et al., 2021).

There may potentially be a saturation point for the number of bees and colonies an area can support and further study would be useful for this area of southern Kenya. Although in Europe, high densities of managed honey bees may harm populations of wild pollinators (Geldmann & González-Varo, 2018) our study exploring this concern (King, Serem & Russo, 2018) showed there was little difference in the abundance, species richness and community composition of wild bee communities around beehive fences.

All the elephant crop-raids recorded occurred at night from early evening (5 p.m.) through to early morning (6 a.m.) as the elephants were clearly wary of entering areas of active human presence during the day. Although honeybees are most active during the day, we regularly witnessed bees flying actively around their hives at night and frequently experienced being stung by bees when fixing hives or harvesting honey in the dark (done to avoid disturbance to farmers during the heat of the day). The presence of any light at all (any moon or torch light) enabled the bees to fly out quite actively at night around the hive and particularly to swarm onto any target of disturbance or warm patch. Frequently our team working in the dark would be covered in swarming bees and one could only imagine how an elephant would react to having a whole swarm of bees land on his warm body after disturbing a hive. As our project site is in the tropics just south of the equator it rarely gets cold enough to cause the bees to hibernate and such ideal altitude and temperature conditions could be a further reason for the deterrent success of beehive fences as conflict mitigation tool.

With climate change predictions for Kenya suggesting that rainfall patterns may change and become more erratic over the next few decades (Doi et al., 2022), this study suggests that the effectiveness of beehive fences and hive occupations will be negatively affected by periods of lower rainfall. In response to this, farmers will have to adapt with more pro-active drought-resilient tactics if their hives are to remain useful such as feeding the bees which conversely will reduce profit margins (Vercelli et al., 2021). Climate change tactics that may include an increased use of new seed varieties and pesticide use to elevate crop growth may also have negative effects on hive occupancy and bee health (Butler, 2019; Kimani, 2017; Newman et al., 2021).

Here we show that properly implemented and maintained beehive fences can be an effective long-term option to reduce human–elephant conflict that show no sign of habituation setting in (King et al., 2010). However, despite acting as a highly effective mitigation method, reliance on a single method has obvious downfalls, with droughts and other uncontrollable events impacting on the hives ability to protect farms, instead a multi-faceted approach is required. This entails multiple approaches being used in combination, or rotation, with beehive fences being used alongside other non-rain fed methodologies such as the use of olfactory or light based deterrents, trenches, and the adoption of drought-tolerant, non-palatable crops such as sunflowers, chillies, ginger, and other spice crops (King et al., 2023; Shaffer et al., 2019).

The reality of HEC mitigation methods like beehive fences is that while they may aid rural farmers, they can act as a “sticking plaster” to the much more complicated, escalating environmental degradation issues caused almost exclusively by excessive human population growth and encroachment into wildlife habitats and corridors through infrastructure development. When combined with extreme changes in climate and land use (e.g., railway lines, roads, deforestation) we are forcing ever more interactions between humans and elephants as foraging land for elephants and space to traverse between dry and wet season locations become ever-more obstructed. Coupled with the increase in livestock numbers and illegal grazing activities both inside national parks and on open rangelands, elephants are losing their strongholds and becoming ever more reliant on the whims of politics. If habitat conversion and connectivity between protected areas continues to decline at the present rate, it is likely that both conflict with humans will increase in the short term but eventually elephants will be extirpated completely from lands outside of nationally protected parks and reserves. Honey bees and the effectiveness of beehive fences are also likely to be equally negatively impacted by such landscape and climate changes unless communities are supported to practice organic farming and are trained in elevated bee husbandry skills. Although beehive fences are not a sole solution to stopping human–elephant conflict, they are an excellent medium for engaging low-income farmers in strategies for self-reliant coexistence that also help promote healthy farming habits within these escalating wider environmental issues.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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