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Research article

Protecting the resource: an assessment of mitigation methods used to protect large trees from African elephant impact in a savanna system

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African elephants *Loxodonta africana* can alter the structural components of savanna ecosystems, often through the reduction of the large tree (≥ 5 m height) cover component. Elephant impact can be amplified in small, protected areas, or areas where water is readily available to elephants. One management option is to protect large trees directly using applied mitigation methods to limit elephant impact. In this paper, we assessed and compared the effectiveness and logistical requirements of four mitigation methods that have been applied to protect large trees from elephant impact in South Africa's Greater Kruger National Park – namely African honeybees *Apis mellifera scutellata* in beehives; creosote oil in glass jars, concrete pyramids arranged in circles around trees, as well as wire-netting the trees' main stems. For each method, elephant impact levels and tree mortality rates were measured over a 2–5-year period depending on the method in use. Sample sizes ranged from 43 to 59 trees per mitigation method, with a comparable control, which was a tree of the same species and morphological dimensions but lacking any mitigation application. Beehives were the most effective method at reducing tree loss, significantly reducing tree mortality from 34% (6.8%/year) in control trees to only 10% (2% $year^{-1}$) over the five-year experimental period. However, beehives were the most expensive method to apply to a tree, although this cost can be compensated through honey sales. Concrete pyramids reduced tree loss when the combined pyramid radius was > 1.5 m in length, whilst wire-netting was effective against bark-stripping by elephants but was still vulnerable to heavier forms of impact such as uprooting and stem snapping. Creosote jars did not prevent elephants from impacting treated trees. Our results provide managers with a toolkit for protecting large trees against elephant impact, commenting on both the efficacy and the logistical constraints for each method.

Keywords: beehives, elephant impact, human–elephant conflict, mitigation measures, tree protection, wire netting

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Introduction

The impact that elephants have on their environment is a contentious subject (Owen-Smith et al. 2006, Edkins et al. 2008, Scheiter and Higgins 2012), as elephants can modify the structural components of their environment, which can both increase and decrease species biodiversity (Pringle et al. 2008, Parker 2019). One such concern which arises from elephant impact is the loss of large trees (≥ 5 m in height, Shannon et al. 2008).

Large trees provide important ecological benefits to savanna ecosystems (Belsky and Canham 1994), creating a cooler, wetter microclimate underneath the canopy layer (Joseph et al. 2018), which provides habitat for more shade-tolerant plant species (Ludwig et al. 2004, Maponga et al. 2021). The root systems of large trees transport nutrients upwards from deeper soil layers, eventually dispersing these nutrients on the soil surface in the form of litter (Ward et al. 2018). This in turn can lead to more nutritious grasses growing underneath the canopy, which attracts grazing herbivores (Treydte et al. 2008). Large trees also serve important habitat functions within ecosystems due to their horizontal and vertical structuring, creating spatial heterogeneity (Dean et al. 1999, Pringle et al. 2016). For tree-nesting fauna species, these trees are important for landscape connectivity (Monadjem and Garcelon 2005), providing a 'life-boating' function for species which would otherwise not exist in that ecosystem (Franklin et al. 1997).

The decline of large trees due to elephant impact is an extensively studied field across the African continent (Leuthold 1977, Gandiwa et al. 2011, Teren et al. 2018, Coetsee et al. 2023, Khosa et al. 2023), and various management strategies have been applied to limit or redistribute the effects of elephants by compelling the elephants to move to different parts of the landscapes both seasonally and temporally (reviewed by Henley and Cook 2019). Elephant impact on large trees can differ in both type and severity, with the main impact-types being bark-stripping, branch breakage, main stem snapping, and uprooting (Walker 1976). Elevated levels of any of all these impact-types can lead to tree mortality (Gadd 2002, Das et al. 2022).

There also exists a human-centric element of aesthetic value of a healthy and functioning ecosystem, and this human perception of what constitutes a healthy ecosystem is often challenged by fallen trees (Edge et al. 2017). Conservation decision-makers are placed under pressure to manage the ecosystem accordingly with stakeholder views, and thus a mild form of human–elephant conflict (HEC) exists regarding elephant impact on large trees (Henley and Cook 2019).

In previous strategies aimed at reducing elephant impact on the environment, elephant numbers have also been decreased by means of culling entire herds of elephants (Whyte et al. 1998), or translocating elephants to other protected areas (PAs) (Grobler et al. 2008). However, modern management practices have moved away from directly managing elephant numbers, towards managing their effects on the ecosystem (Ferreira et al. 2011). In large and open systems, elephant impact on large trees has been managed through environmental manipulation strategies acting at a landscape level, such as by the closure of artificial waterholes (Purdon and Van Aarde 2017). Limiting the availability of waterholes can help create a gradient of varying elephant impact levels on trees, where trees closer to the remaining waterholes are expected to receive higher levels of impact in comparison to trees further away from a waterhole (Gaylard et al. 2003, Van Langevelde et al. 2017).

However, in small PAs, or PAs with an abundance of water, it can be difficult to manage elephant impact both spatially and temporally to create a heterogenic spatial and temporal distribution of elephant impact (Ferreira et al. 2017, Abraham et al. 2021). For these PAs, directly protecting the tree from elephants by using mitigation methods is a management option (Henley and Cook 2019). This targeted strategy gives decision-makers the choice to directly select which individual trees require protection, and then to apply a suitable mitigation method. However, whilst a variety of mitigation methods have been implemented to protect large trees from elephant impact, only a small number of scientific studies have been conducted to test the efficacy of some of these methods (Derham et al. 2016, Cook et al. 2018). Further studies are thus required to assess the various tree protection methods available to decision-makers, to review and compare the efficacy and logistics involved with the proposed methods.

South Africa's Associated Private Nature Reserves (APNR) within the Greater Kruger National Park (Greater KNP) provides an ideal experimental site to compare mitigation method efficacy and logistics, as it is a landscape where water is readily available to elephants (Linden et al. 2022). Both repellent and barrier-forming methods have been used in the APNR to protect large trees from elephant impact. Repellent methods serve to lessen the time that an elephant spends around a tree, thereby reducing the probability of impact (O'Connor et al. 2007). Repellent methods include the hanging of active beehives from trees' branches (termed 'beehives'), as well as glass jars containing creosote oil attached to the main stems of trees (termed 'creosote jars'). Barrier-forming methods serve to create an obstacle between the elephant and the tree. These include the placement of concrete pyramids (base length of 20 cm and height of 20 cm) in circles around the main stem of the tree (termed 'pyramids'), as well as placing chicken-mesh wire around a tree's main stem to prevent bark-stripping (termed 'wire-netting').

In this paper, we review these four mitigation methods which have been used to protect large trees from elephant impact in the savanna system of the APNR. Our objectives were 1) to assess the effectiveness of each mitigation method against various elephant impact-types; 2) to assess the survival rates of trees with each mitigation method in comparison to control trees; and 3) to evaluate the annual costs and logistic requirements for maintaining each mitigation method.

Material and methods

Study site and tree species

The study was conducted in the APNR, a privately-owned PA sharing an open boundary with the Greater KNP in South Africa's north-eastern region (24°04–24°55S; 30°82′–31°48′E, Fig. 1). The APNR is comprised of smaller PAs, of which three of these were used for testing mitigation methods, namely Ingwelala Private Nature Reserve (Ingwelala), Jejane Private Nature Reserve (Jejane), and N'tsiri Private Nature Reserve (N'tsiri) (Fig. 1). The APNR is located within the broad Savanna Biome of South Africa, with Ingwelala and N'tsiri occurring within the *Combretum*/*Colophospermum mopane* woodland vegetation unit, whilst Jejane is within the mixed *Combretum*/*Terminalia sericea* woodland vegetation unit (Mucina and Rutherford 2006). The APNR falls within the 300–500 m altitude range, with a mean annual temperature high of 22°C (Greyling 2004, Peel et al. 2007).

All four mitigation methods were assessed on adult *Sclerocarya birrea* A. Rich. trees (marula). *Sclerocarya birrea* is a deciduous keystone species, with both ecologic value and economic uses (Shackleton et al. 2002). Listed as a protected tree species in South Africa (Shackleton and Shackleton 2005), it is also a highly sort after tree species by African elephants (Jacobs and Biggs 2002, Helm and Witkowski 2013). Elevated levels of elephant impact can lead to the decline of adult *S. birrea* numbers in PAs (Cook et al. 2017), and elephants have been found to select for *S. birrea* above many other savanna tree species, especially by bull elephants which are known to impact trees more severely (Greyling 2004, Abraham et al. 2021). *Sclerocarya birrea* is therefore an ideal large tree species on which to assess elephant mitigation methods, as it is a proven important food source to elephants (Greyling 2004, Shannon et al. 2008).

At all three study sites, control trees were selected at a minimum distance of > 5 m from a mitigation tree. This was specifically done to reduce the probability of a tree with a beehive (repellent method) reducing the likelihood of a nearby control tree receiving elephant impact, as elephants have been found to approach active beehives within 3–5 m before being deterred (King et al. 2017, Cook et al. 2018). This distance was then standardised for the four mitigation methods.

Mitigation method descriptions and layout

Beehives

Beehives have been used as a mitigation method for promoting human–elephant co-existence in both Africa (King et al. 2017) and Asia (van de Water 2020), where the honeybees inside of beehives protect crop fields against elephant crop raiding events. Elephants are sensitive to the stings of honeybees around their ears, eyes, and inside of their trunks (Vollrath and Douglas-Hamilton 2002). Elephants also display a fearful retreating response to the sounds of swarming honeybees (King et al. 2018), as well as honeybee alarm pheromones (Wright et al. 2018).

Between November 2015 and November 2020, 50 *S. birrea* trees containing beehives with the *Apis mellifera scutellata* subspecies were monitored for elephant impact in Jejane, alongside 50 *S. birrea* control trees (Fig. 1, Supporting information). Two beehives were hung on the opposite sides of the main stem from the extended branches of each tree (Cook et al. 2018, Supporting information). Beehives were hung 2 m above the ground, roughly at the eye-level for an adult elephant (Vollrath and Douglas-Hamilton 2002) and

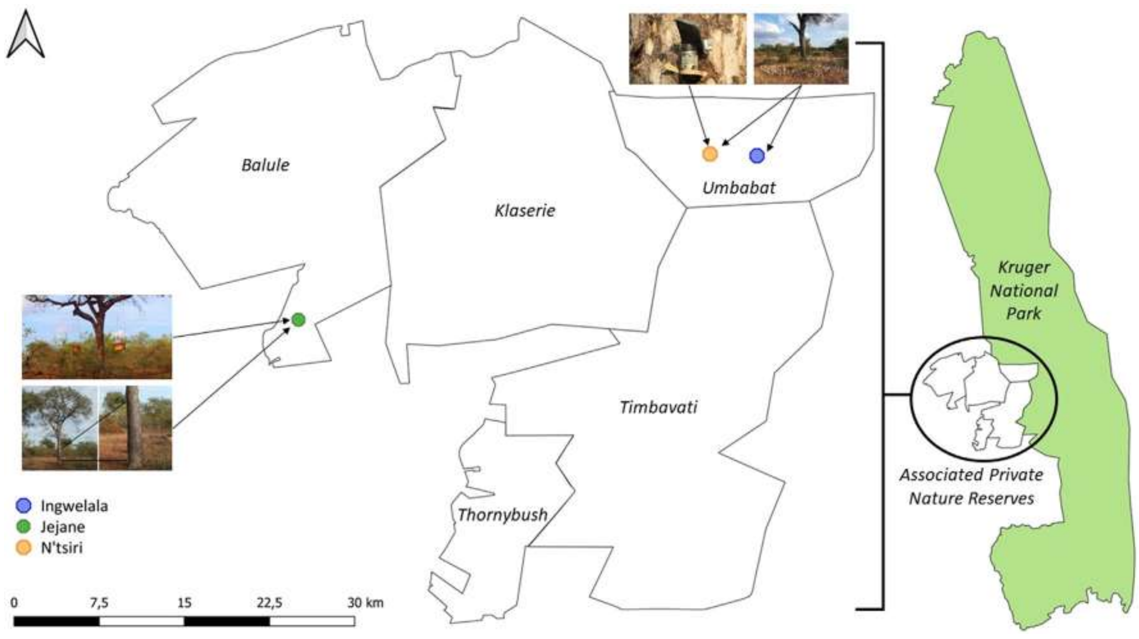

Figure 1. Location of the three tree study sites within the Associated Private Nature Reserves (APNR), South Africa.

were connected to nylon ropes. Plantex glue was spread along the ropes to prevent ants from entering the beehives. Beehive occupancy was assessed monthly. During May – September of each year, the driest months of the year, the beehives were given artificial pollen and nectar to minimize absconding events. Beehives that went inactive during the study period were left hanging in the trees to assess how the elephants responded to the presence of the vacated beehives alone after the colony had absconded.

Creosote oil in jars

Private landowners deployed the creosote method, with Elephants Alive asked to monitor the effectiveness of the method after its implementation. This method is based on anecdotal information that the smell of creosote is unappealing to elephants, and thus can serve as a repellent method to protect large trees from elephant impact. Creosote is a residue created by the distillation of coal-tar (Choudhary et al. 2002). It has a thick and oily composition, is highly flammable, and does not easily dissolve in water (Van Zyl 2013). Furthermore, creosote has carcinogenic properties due to presence of polycyclic aromatic hydrocarbons and phenolic compounds (Jurys et al. 2013). To our knowledge, no previous scientific studies have assessed whether creosote is an effective elephant mitigation method.

Between January 2018 and December 2019, 67 *S. birrea* trees containing creosote jars were monitored for elephant impact in N'tsiri (Fig. 1, Supporting information). This mitigation project was set up by N'tsiri management. Due to the limited availability of control *S. birrea* trees within the study site, a total of 59 were located and monitored. The following set up was applied to a creosote tree: a 300 ml glass jar was filled with creosote oil (*Powafix* brand). The jar was attached to the tree's main stem by hammering two nails into a tin strip around the jar, 1.5 m above the ground (Supporting information). A second tin roof-strip was placed above the jar to prevent rainfall from filling up the jar (Supporting information). Trees containing creosote were only assessed for a period of two years due to the respective management structure removing all the jars by the end of 2019.

Pyramids

Concrete pyramids, placed in rings around a tree's main stem, have been used to create a barrier between the tree and elephants (SANParks 2012). This method is a modification of the use of natural rocks to create a barrier between elephants and a desired resource to promote human–elephant co-existence (Fernando et al. 2008). However, to our knowledge, there have been no scientific studies performed to quantify the effectiveness of concrete pyramids as a mitigation method to protect trees against elephant impact.

Between January 2018 and December 2020, 43 *S. birrea* trees, encircled by rings of concrete pyramids extending away from the trees' main stems, were monitored for elephant impact at Ingwelala and N'tsiri (Fig. 1, Supporting information). This mitigation method project was set up by the management of Ingwelala and N'tsiri. An additional 59 *S. birrea* were used as control trees. All pyramid base lengths were 20 cm, and 20 cm in height, with each pyramid having a surface area of 400 cm^2, and approximate mass of 3 kg. Pyramids were placed next to one another in rings around each tree's main stem. A distance space of 0.5 m was left between the tree's main stem and the first circle of pyramids (inner gap, Fig. 2). However, the pyramid radius (i.e. the distance barrier created between an elephant and the inner gap, Fig 2) varied between individual trees (range: 0.56–2.5 m).

Due to the variation in pyramid arrangement around each tree, we calculated the mean surface area covered by the pyramids around each tree by firstly measuring the total radius length of the pyramids (tree stem to outer pyramid, Fig. 2) across eight cardinal direction points around the tree and averaging this measurement (mean total radius). We then used the following formulae to calculate the pyramid surface area (m^2) around each tree:

$$\text{Full surface area of pyramids and inner gap around tree } (A) = (\pi)(\text{mean total radius})^2$$

$$\text{Inner surface area } (B) = (\pi)(\text{inner gap radius})^2$$

$$\text{Pyramid surface area } (m^2) = A - B$$

Wire-netting

Wire-netting involves wrapping chicken-mesh around a tree's main stem to protect it from bark-stripping by elephants by creating a barrier around the stem (Derham et at. 2016). Wire-netting has been found to prolong the survival rates of large trees (Derham et al. 2016), as trees are less likely to die from the aftermath effects of bark-stripping such as insect infestation (Wigley et al. 2019) and desiccation after fires (Das et al. 2022). However, these trees are still vulnerable to

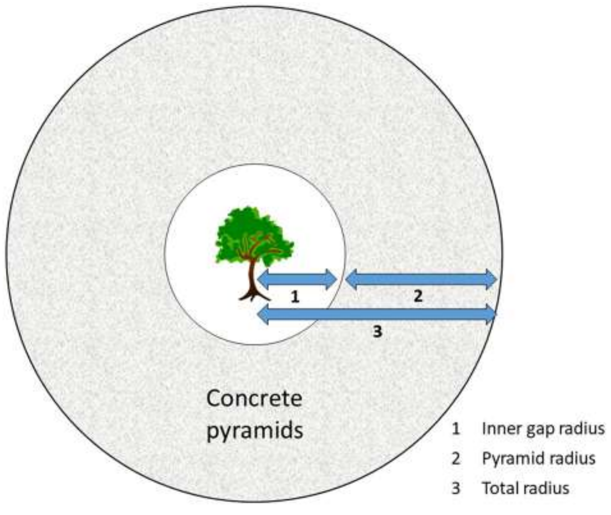

Figure 2. Illustration of the measurements taken for each pyramid tree in the Associated Private Nature Reserves (APNR).

heavier forms of elephant impact such as stem snapping and uprooting (Henley 2013, Cook et al. 2018).

Between November 2015 and November 2020, 50 wire-netted *S. birrea* trees were monitored for elephant impact in Jejane, alongside 50 *S. birrea* control trees (Fig. 1, Supporting information). This experimental research project was set up by Elephants Alive NPC as part of a MSc dissertation, where 1.8 m of 2 mm chicken mesh wire was wrapped around the main stem of large trees (Cook et al. 2018). The chicken mesh was placed 0.5 m above the ground, stretching up to 2.3 m in total height. The chicken mesh was wrapped around the tree twice to provide the tree with a double layer of protection, with a 50 cm overlap to accommodate any expansion of the tree's main stem. Five galvanised U-shaped nails were placed down the overlapped section to secure the chicken mesh to the tree. Where the chicken mesh covered holes/groves along the main stem, a hole was cut in the mesh to ensure no small animals would be trapped underneath the mesh.

Field assessments

Baseline field assessments were first conducted on all selected *S. birrea* trees with the following data being recorded: stem diameter at breast height (DBH) (cm), and tree height (m) using the *VolCalc* software program for measuring tree morphometrics (Barrett and Brown 2012). Elephant impact scoring methods, as developed by Walker (1976) and modified by Greyling (2004), were used to assess elephant impact for the following impact-types: bark-stripping, primary branch breakage, secondary branch breakage, main stem snapping, and uprooting (Table 1). Trees which contained fruit in the canopy, or had fruit kernels underneath the canopy, were recorded as female trees, whilst those large enough to be reproductively mature but without fruit or kernels were recorded as male trees (Helm and Witkowski 2012). Following the baseline assessment, each tree was assessed on an annual basis, where the same impact scores were re-assessed to evaluate whether the scores had increased following additional elephant impact, as well as to assess the survival status (alive/dead) of each tree.

The resilience of each mitigation method was also assessed. This included the following per mitigation method – 1) beehives: whether the tree's beehive was active or not; 2) creosote: whether the jar was still attached to the tree's main stem, or had been broken and spilt onto both the tree and the soil; 3) pyramids: whether the pyramids were arranged in tight formation around the tree, or had been shifted by elephants to reach the tree; and 4) wire-netting: whether the wire-netting was still in a rigid formation around the tree's main stem, or had been torn off by an animal or split by the growth of the tree's main stem.

Financial costings

Financial data for the set up and maintenance of the beehives and wire-netting were provided by Elephants Alive. For the beehives, this included the costs of the beehives, beehive

Table 1. Elephant impact scoring system for impact on large trees, as defined by Walker (1976) and modified by Greyling (2004).

Impact-type	Impact-type severity classes									
	1	2	3	4	5	6	7	8	9	10
Bark-stripping	No impact	< 1%	1–4%	5–10%	11–25%	26–50%	51–75%	76–90%	91–99%	100%
Primary branch breakage	No impact	> 0–25%	26–50%	51–99%	100%					
Uprooting	No impact	Tree alive, roots in ground, just leaning over (> 0–25%)	Tree pushed onto ground but is alive and has all roots in ground (26–50%)	Tree alive but has half of the roots in the ground and half of the roots exposed in the air (50–99%)	Tree has been uprooted (all the tree's roots are in the air) (100%)					
Main stem snapping	No impact	Main stem has been snapped but is in a re-coppicing state (> 0–25%)	Crown of tree is still attached to the main stem and the tree is still alive (26–99%)	Tree is still alive but not in a re-coppicing state (50–99%)	Tree has subsequently died from main stem breakage (100%)					
Secondary branch breakage	No impact since baseline assessment	New impact since baseline assessment								

hanging material, purchasing of a live *A. m. scutellata* colony, a bee suit with gloves and boots, *Plantex* glue, as well as artificial nectar and pollen to feed the bees during the winter. As beehives can be used for honey production, financial income data was provided by Elephants Alive for potential income per beehive. For wire-netting, financial data included the purchasing of chicken mesh and U-shaped nails. N'tsiri kindly provided financial data for the set up and maintenance of the creosote jars and the pyramids. For the creosote jars, this included the purchasing of creosote oil, a glass jar, tin material, as well as nails. For the pyramids, costs included the concrete and the mould to build each pyramid. All financial data was recorded in US Dollars (exchange rate: 1 ZAR to $18) (Exchange Rates UK 2023) and calculated over one- and five-year time periods per mitigation method. Cost of travel to set up the experimental site and monitoring were not included as the distances varied between sites.

Statistical analyses

All statistical analyses were conducted using R ver. 4.2.1 (www.r-project.org), with a significance level of $p < 0.05$. We constructed four classification trees (CT), based on conditional inference, to understand how different environmental variables influenced the probability of tree survival for each mitigation method ('party' package, Hothorn et al. 2006). Classification trees were constructed with tree survival (binomial) as the dependent variable on the following independent variables: presence of a mitigation method (categorical), tree sex (categorical), DBH (continuous), and tree height (continuous).

We used Fisher's exact test to investigate whether there was a significant difference between the proportion of dead mitigated and control trees for each mitigation method. Multiple logistic regression models were used to test for the significance of treatment, tree height, and tree diameter at breast height as predictor variables of tree mortality for each mitigation method. Whilst a positive correlation exists between tree height and tree diameter at breast height, it was weak for all four mitigation methods (Beehives: $r = 0.38$; Creosote: $r = 0.62$; Pyramids: $r = 0.48$; Wire-netting: $r = 0.41$) and so both factors were used for the multiple regression models.

We performed Kaplan-Meier log-rank survival analyses ('survival' package, Therneau 2023) to test for significant differences between the survival probabilities of the mitigated and control trees for each mitigation method. We did not run survival analyses between the mitigation methods due to the variation in time frames at each study site and locality, which was beyond the control of our study (Table 1). We were therefore interested in comparisons between each mitigation method its control counterparts, and not between sites and mitigation methods. For the survival analyses, tree death was considered truncated (1), whilst a surviving tree was considered censored (0) (Therneau 2023).

Due to non-normality of the elephant impact-type scores, Wilcoxon signed-rank tests were used to test for significant changes in median impact scores (baseline and final assessment) for each elephant impact-type per mitigation method (Table 1). For pyramids specifically, we also performed a Welch's t-test to assess whether there was a significant difference between the mean pyramid radius (Fig. 2) of the pyramid-treated trees which were alive and dead. We then ran a correlation between the pyramid radius of the living trees with pyramids and the pyramid surface area of surviving pyramid trees to calculate the 'ideal' number of pyramids required to protect a tree.

Results

Beehives

Beehive mean annual occupancy ranged from 3.5 to 100% throughout the five-year study duration, with the number of active beehives decreasing over the years due to factors such as ant invasions, lack of forage availability, and intense winds (Fig. 3). The large reduction in the number of active beehives between 2017 (21.9% occupancy) and 2018 (3.5% occupancy) was due to Elephants Alive removing active beehive colonies to a new site with a greater abundance of floral resources before the 2018 dry season. This was done to prevent colonies from rapidly absconding from their beehives. These active beehives were then replaced with inactive beehives. The increase in active beehives from 2018–2020 were from the natural colonisation of beehives by wild African honeybee swarms.

The presence of beehives in trees significantly decreased the likelihood of tree mortality (Fisher's exact test: $p = 0.007$), and according to the CT analysis, the presence of a beehive in a tree was the only significant variable affecting tree mortality probability at Jejane ($p < 0.05$). After five years, 10% of the beehive trees had died, at an annual tree mortality rate of only 2% per year (Supporting information). This was 3.4 times less in comparison to the control trees (Supporting information). Secondary branch breakage was the most common elephant impact on beehive trees, whilst control trees had significant increases in the impact scores of all impact-types except for uprooting (Supporting information). According to the multiple regression analysis, tree mortality probability was significantly decreased with both the presence of beehives ($Z = 2.25$, $p < 0.05$) and an increase in tree height ($Z = 2.72$, $p < 0.001$) (Supporting information). Beehives also significantly improved the survival probabilities of trees across the five-year study period (Log-Rank test $= 7.675$, $df = 1$, $p < 0.05$; Fig. 4a).

Whilst no active beehive was ever tampered with by elephants during the study, we did find that 14 inactive beehives were opened or pulled down by elephants in the final two years of the five-year study (Fig. 5a). A further two beehives fell and broke after a major windstorm in 2019. Financially, beehives were the most expensive method to set up and maintain per tree ($170), with the highest maintenance costs occurring during the dry months when artificial feeding was required, as natural forage availability for the honeybees was low (Table 2). Beehive costs could range as high as $280 if larger, higher quality beehives were required for honey production (Elephants Alive pers. comm.), with Elephants Alive recording an annual

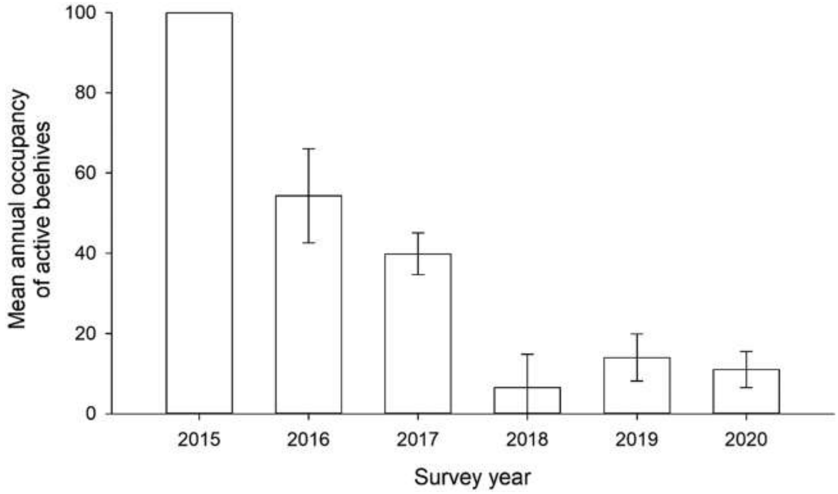

Figure 3. The annual mean number of active beehives (percentage (%) ± monthly standard deviation) in the study site within Jejane Private Nature Reserve.

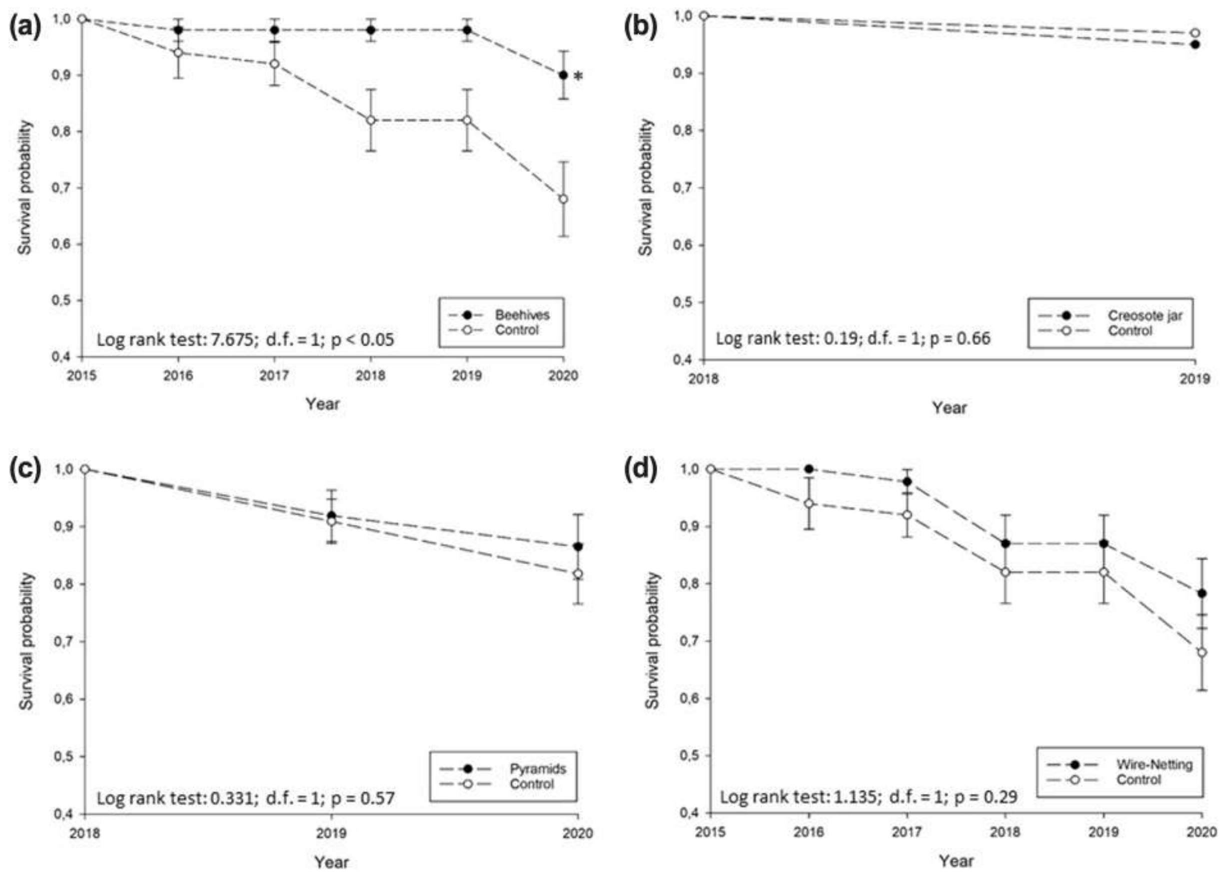

Figure 4. Survival probability (probability ± SE bars) of (a) *Sclerocarya birrea* trees protected by beehives (2015–2020), (b) creosote (2018–2019), (c) pyramids (2018–2020) and (d) wire-netting (2015–2020), alongside their control counterparts, in the Associated Private Nature Reserves (APNR), South Africa. Asterix symbol represents a significant difference ($p < 0.05$) in survival probabilities between the treatment and its respective control by the end of the trial.

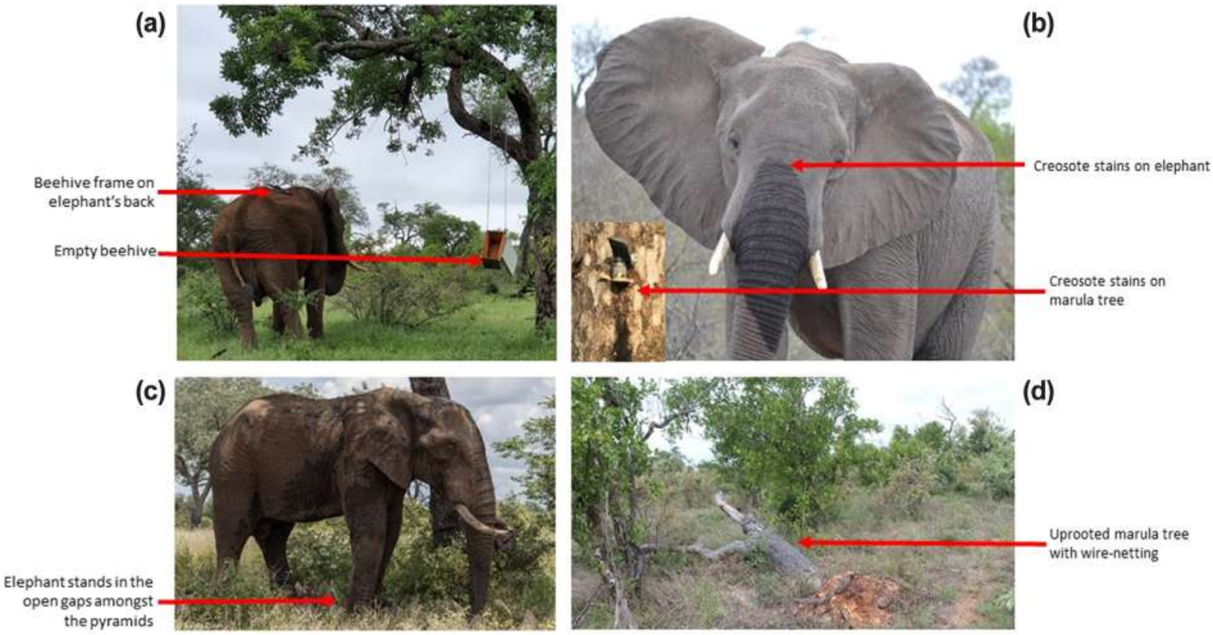

Figure 5. Examples of when (a) beehives, (b) creosote tins, (c) pyramids and (d) wire-netting are not effective against mitigating elephant impact on large tree species.

income of $78 per beehive for the duration of this study through the production and sales of honey, and hence potentially recouping the original outlay in five years.

Creosote jars

The presence of creosote jars did not significantly influence the likelihood of tree mortality in comparison to control trees (Fisher's exact test: $p=0.84$). The CT analysis did not find any significant variables to explain tree mortality between creosote and control trees, whilst the multiple regression did not find either the presence of a creosote jar in a tree, nor height, to significantly influence tree survival probabilities (Supporting information).

Bark-stripping was the most common elephant-impact type recorded on both the creosote and control trees, with significant increases in the impact scores for both creosote and control trees over time (Supporting information). Creosote trees also had a slightly higher annual mortality rate in comparison to control trees (Supporting information), although there was no significant difference between the survival probabilities of control and creosote trees (Log-Rank test $=0.019$, $df=1$, $p=0.66$; Fig. 4b).

After one year of study, 17 (25%) of the 67 creosote trees were broken by animals or potentially high gusts of wind. We observed elephants with creosote stains on their bodies, whilst creosote spillage was also seen on the trees' main stems (Fig. 5b). Financially, creosote jars were the cheapest mitigation method to set up and maintain per tree (Table 2), however, costs would increase if the glass jars were continuously broken by elephants, as observed after the one-year study.

Pyramids

The presence of pyramids around a tree's main stem did not significantly affect the tree's likelihood of mortality over the two-year study (Fisher's exact test: $p=0.98$). There were significant increases to the bark-stripping scores on both the pyramid and the control trees over time, as the elephants were still able to reach the trees' main stems from the outskirts of the pyramids. However, heavier impact-types such as main stem snapping and uprooting tended to be more prevalent on control trees, although this difference was not significant (Supporting information). Neither the CT nor the multiple regression analyses found the presence of pyramids, nor tree height, were significant factors affecting tree mortality (Supporting information), and the survival analyses found that there was no significant difference between the survival probabilities of control and pyramid trees (Log-Rank test $=0.331$, $df=1$, $p=0.57$; Fig. 4c).

However, we found that pyramid trees which were still alive had a mean pyramid radius and standard deviation of 148 ± 25 cm, which was significantly longer than those of dead pyramid trees (129 ± 9 cm; $t_{(38)}=3.773$, $p < 0.001$). This equated to a mean pyramid surface area of 14.36 m^2 around a tree, and thereby 109 pyramids required per tree (if pyramids are 400 cm^2 at the base). Combined with the 50 cm gap between the tree and the first ring of pyramids, this results in a distance barrier of almost 2 m required between the elephant and the tree's main stem. However, even if the distance barrier was achieved, the pyramids were still required to be packed tightly, or else the elephants were able to push pyramids aside or stand in gaps amongst the pyramids (Fig. 5c). According to the financial analysis, pyramids were

Table 2. Cost–benefit analysis of each of the four mitigation methods used to protect *Sclerocarya birrea* trees from elephant impact in the Associated Private Nature Reserves (APNR), South Africa.

	Cost items	Predicted annual cost per tree	Predicted five-year cost per tree	Advantages	Disadvantages	Logistical notes
Beehives	Beehive (wooden)	$50	$50	Highly effective against all forms of elephant impact	Bee colony may abscond, after which a new colony may need to be purchased if no wild bee swarm is caught	Recommended small-scale usage in comparison to other mitigation methods
	Beehive colony	$35	$35			
	Nylon rope	$2	$5	Both active and inactive beehives can be used together to increase the number of protected trees	Fires around beehives may lead to the colony absconding	A trained beekeeper should conduct beehive installation and maintenance. Additional costs may occur if a full bee suit and gumboots are required ($130)
	Plantex glue[1]	$3	$15			
	Artificial pollen[2]	$45	$135	Beehive expenses can be supplemented through the sale of honey and other bee-related products	Beehives need continual maintenance, particularly when forage resources are low (seasonal effect)	Reapplication of Plantex glue once a year, and potentially more following heavy rains
	Artificial nectar[3]	$35	$110		Beehives do not protect neighbouring trees outside a 5m radius	Artificial pollen and nectar annual usage may vary, depending on rainfall and flower availability
	Total	**$170**	**$350**		This is the most expensive method of the four mitigation methods to implement	African honeybees can be aggressive pollinators and may exclude other pollinator species (Martins 2004)

(Continued)

Table 2. Continued.

	Cost items	Predicted annual cost per tree	Predicted five-year cost per tree	Advantages	Disadvantages	Logistical notes
Creosote jars	Creosote oil[4]	$1	$5	Cheapest of the four mitigation methods	Elephants have been observed breaking creosote jars, leaving glass on the ground and creosote stains on both the elephants and the trees	Jars need a tin roof over the top to prevent the creosote oil from flowing out during rains
	Glass jar (300 ml)	$1	$1			
	Tin strips	$2	$10	Method is not affected by seasonal environmental changes	Creosote stains on trees lasts longer than two years (personal observations)	Spillage of creosote oil into the soil should be reported to reserve management
	Total	**$4**	**$16**		Creosote oil is an environmental pollutant and has carcinogenic properties	Our results recommend that this method is not suitable for tree-protection purposes
Concrete pyramids	Concrete pyramids (x109 minimum)	$35	$35	Minimal maintenance required once pyramids have been correctly arranged around the tree	Labour intensive to set up, which may limit the scale of usage of this method	Pyramids need to be tightly arranged to prevent elephants from stepping between pyramids and should be monitored thereafter
				Pyramids can last > 10 years once arranged (personal observations)	If pyramids are not arranged tightly and the radius is too short, elephants can still reach the main stem of a tree	
	Total	**$35**	**$35**	Method is not affected by seasonal environmental changes	If gaps between pyramids exist, elephants can move pyramids around with their feet	Pyramids can be replaced by natural rocks, however, the effect of the removal of many rocks on native fauna requires investigation

(Continued)

Table 2. Continued.

	Cost items	Predicted annual cost per tree	Predicted five-year cost per tree	Advantages	Disadvantages	Logistical notes
Wire-netting	1.8 m of 13 mm chicken mesh	`	S26	Wire-netting is relatively cheap and easy to place around a tree's main stem	Wire-netting loses its effectiveness on smaller trees which are more vulnerable to stem snapping and uprooting	Calculated on an average tree stem diameter of 40 cm
	U-shaped nails (25 mm)[5]		$2	Potential large-scale application due to price and relative effectiveness	Wire-netting may need replacement after 4–5 years	Ensure that there is a finger's gap between the chicken mesh and the main stem so that the mesh is not too tight
	Total	**$14**	**$28**	Method is not affected by seasonal environmental changes	Wire netting could prove challenging for multi-stemmed trees	Chicken mesh may need to be replaced after 4–5 years, using small chicken mesh (e.g. 13 mm diameter) to prevent elephants from ripping off the mesh with their tusks together with other factors that influence general deterioration (rust as an example) and structural integrity of the mesh around the tree (Cook et al. 2023)

[1]Calculated from the purchase of 20 kg of Plantex glue ($35); [2]Calculated from the purchase of 10 kg of artificial pollen; [3]Calculated from the purchase of 10 kg of artificial nectar; [4]Calculated from the purchase of five litres of creosote tar oil; [5]Calculated from the purchase of 100 U-shaped nails.

the second most expensive mitigation method to implement per tree (Table 2).

Wire-netting

The presence of wire-netting did not significantly influence a tree's likelihood of mortality during the five-year study period (Fisher's exact test: $p=0.9$). The most frequent elephant impact-types on wire-netted trees were secondary branch breakage, > main stem snapping and > primary branch breakage, all of which had significant increases in their impact scores (Supporting information). Wire-netting was, however, particularly effective against bark-stripping, with only 4% of the wire-netted trees being bark-stripped across five years in comparison to 32% of the control trees. Impact scores significantly increased for all impact-types on control trees, apart from uprooting (Supporting information).

Tree height was the only significant variable influencing wire-netted tree survival according to both the CT ($p < 0.05$) and the multiple regression analyses ($Z = 1.99$, $p < 0.05$; Supporting information). The CT analysis found that trees > 7.81 m in height had a significantly higher survival probability in comparison to trees lower than this height ($p < 0.05$). Wire-netted trees had a higher probability of survival in comparison to control trees across the five-year study (0.78 vs 0.68 respectively), though this was not significant according to the survival analyses (Log-Rank test=1.135, df=1, $p=0.29$; Fig. 4d). Wire-netted trees were still vulnerable to more severe elephant impact-types such as main stem snapping and uprooting (Fig. 5d). Financially, wire-netting was the second least expensive mitigation to implement, with small cost variations being based on the size of the tree's main stem diameter, as well as the potential need for replacement of the chicken-mesh 4–5 years after deployment (Table 2).

Discussion

Mitigation method efficacy and logistics

Beehives

Beehives proved to be the most effective mitigation method at protecting large *S. birrea* trees from elephant impact in the APNR, however, this was also the most expensive method to implement. The effectiveness of *A. m. scutellata* as an elephant deterrent is well documented (King et al. 2017), and to our knowledge, this is the longest known study to assess the effectiveness of beehives at protecting large trees from elephant impact (Vollrath and Douglas-Hamilton 2002, Ngama et al. 2016, Cook et al. 2018).

Considering that the mean occupancy level for the beehive site was 26.4%, and only 10% of the trees with beehive died from elephant impact over a five-year period, our results also suggest that inactive beehives can serve as elephant deterrents, at least when with the presence of active beehives. However, our results suggest that this deterrent effect may decline once elephants learn that an empty beehive box is not a threat, and so the temporal period of the deterrent effect on elephants may be limited if not accompanied by active beehives to reinforce the stimuli. The encouraging effectiveness of beehives, particularly active beehives, at protecting large trees against elephant impact supports its usage.

Bark-stripping was prevented altogether on the trees with beehives (Supporting information), with our results suggesting that elephants may avoid standing around the main stem of a tree with a beehive, preferring instead to feed on the smaller branches further away from the beehives where they may feel safer. This is important as *S. birrea* can usually withstand branch breakage if < 75% of the branches are broken, and smaller branches can always regrow (Jacobs and Biggs 2002). We suggest that beehives may play a crucial role in preventing heavier impact from elephants to large trees, thus improving tree survival rates.

The results of Elephants Alive's honey sales show that the financial costs of setting up a beehive in a tree could be recuperated five years from project setup. A high selling price may be set for this natural, (organic) conservation-orientated honey. For this study, the costs of all the beehives were sponsored by donors 'adopting' a hive. Projects run by charities therefore have the potential to offset costs.

However, both the logistical (Table 2) and potential environmental concerns (Martins 2004) surrounding the large-scale application of beehives limits this method to a small scale where the beehives can be actively managed. Furthermore, the predicted 2023 El Niño for southern Africa would also increase the difficulty of expanding the beehive project due to lower-than-expected rainfall (ECERA 2023). Conservation managers may wish to invest in a small number of beehives which may be highly effective at protecting selected ecologically or aesthetically important individual trees. Alternatively, beehives could also be moved around a PA periodically during the wet season to increase the impact of the beehives, if the distance moved is greater than 1.5 km from the original tree to prevent the honeybees from flying back to their original tree (Free 1958).

Creosote jars

Creosote jars were the least expensive method to implement, however, they were ineffective at protecting trees from elephant impact and were the only tested method to have a lower survival rate in comparison to their control trees. In Zimbabwe, creosote oil has been assessed as an olfactory deterrent for elephants as part of a 'virtual fence dynamic', where the repellent smell of the creosote oil has shown potential for deterring elephants from crop raiding (La Grange et al. 2022). This effect though, may have been heightened as elephants undertaking crop raiding activities typically have elevated stress levels in comparison to when in the safety of a protected area (Ahlering et al. 2011, Hunninck et al. 2017), and may therefore be more likely to be deterred by unfamiliar stimuli.

Our data suggests that elephants in our study were not deterred by the smell of creosote, and any potential suspicion or fear of the smell was disregarded by the elephants soon after application. This study was the shortest in duration of the four mitigation methods, resulting in only a small number of recorded dead creosote and control trees on which to draw conclusions. However, with 25% of the monitored trees having had their creosote jars broken within the first year of the study, our results suggest that there was no olfactory deterrent. Given the environmental concerns of spilt creosote oil in protected areas (Van Zyl 2013), as well as the lack of supporting evidence that creosote can protect trees from elephant impact, we recommend that this method is not applied to protect trees. Importantly, the study site where our assessments took place immediately removed the creosote jars following the completion of our assessments.

Pyramids

To our knowledge, this was the first study to focus on pyramids as a mitigation method for tree protection against elephant impact, and our results suggest that this method can be effective, but only when the correct distance barrier is created between the elephant and the tree's main stem. We found a large variation in the pyramid radius and stacking formation around the assessed trees, making the overall survival rates of trees with pyramids difficult to assess.

However, this method has been listed as a potential tree protection method by the South African National Parks (SANParks 2012), and if implemented correctly, may be an effective tree protection method. If correctly arranged around a tree, pyramids can prevent elephants from getting sufficiently close to push the tree over, thus restricting elephants to feeding off branches, similar to what was observed with the beehives, and hence generally reduce tree mortality (Jacobs and Biggs 2002). Pyramids should, however, be occasionally monitored to ensure that they have not been re-arranged by elephants. Pyramids or sharp rocks are recommended as a method to reduce other forms of HEC in both Africa and Asia, although the implementation of the method has been described as both time-consuming and labour-intensive (Osei-Owusu 2018). This may limit the scale at which this method can be used for tree protection. However, as the method requires little maintenance after implementation, it can still be an effective method for protecting selected large trees within a protected area, pending the financial and logistical resources of a protected area.

Wire-netting

Wire-netting was both the second most effective mitigation method for prolonging trees survival and to implement. Previous studies have illustrated that wire-netting can be effective at protecting trees from bark-stripping, and thereby potentially improving tree survival (Henley 2013, Derham et al. 2016). Our results, however, suggest that wire-netting loses its effectiveness for smaller trees, particularly in the 5–8 m height category, as these trees are still vulnerable to heavier elephant impact-types such as uprooting and stem snapping (Helm et al. 2009).

Recent research has shown that wire-netting is most effective on trees with a DBH of $\geq$ 40 cm (Cook et al. 2023a). Wire-netting is not a fear-based or repellent method, and elephants are still capable of walking up to the tree and pushing them over. Therefore, given the relatively low financial costs involved with wire-netting trees, it can be a highly effective method if used for larger trees that elephants cannot push over, thereby minimising bark-stripping by elephants and eventual tree death through desiccation (Jones et al. 2022), insect invasion (Wigley et al. 2019), and vulnerability to fire (Das et al. 2022).

The low financial costs also make this method attractive for a larger scale of implementation in comparison to beehives and pyramids. Importantly though, wire-netting still requires maintenance/replacement over time, of which failure to do will lead to a decrease in the wire-netting's effectiveness (Cook et al. 2023a). We also suggest that the smaller chicken-mesh (13 mm), double-wrapped around the tree, is effective as elephants do not appear to be able to place their tusks within the mesh's holes to rip it off the tree.

Combining methods and future research directions

Whilst we have focused on the effectiveness of each mitigation method as a stand-alone method, there is a potential to combine methods to increase tree protection. An integrated management approach, whereby mitigation methods complement one another, could prove highly effective at increasing tree survival.

We also suggest that methods may require further refinement to improve their efficiency. For pyramids, our results have suggested that arranging pyramids tightly together and ensuring a $\geq$ 2 m distance between an elephant and the tree's main stem would be the most effective implementation of that method. For beehives, the use of more expensive but longer lasting beehives may improve occupancy levels. And for wire-netting, the use of stronger wire, albeit of the same dimensions, may reduce the need to replace wire-netting every 4–5 years.

There is also the potential to test and integrate new mitigation methods which have been used for other HEC scenarios, such as honeybee alarm pheromones (Wright et al. 2018), honeybee buzzing sounds (King et al. 2007), chili paste/oil (Osborn and Rasmussen 1995), reflective metal strips (Corde 2022), and 'smelly' elephant repellent (Tiller et al. 2022). Importantly, as we have demonstrated in our field trials, mitigation methods for tree protection require basic experimental design to ensure that accurate assessments are made for method effectiveness, else method success may be inaccurately concluded against no comparison.

Future research into stakeholder perceptions regarding the use of mitigation methods for large tree protection should also be considered. Support for various elephant management strategies, such as the use of tree protection methods, may differ amongst stakeholder groups (Edge et al. 2017), and hence these views will need to be considered when contemplating using tree protection methods. Furthermore, careful consideration should also be taken regarding which tree species and size classes may require protection.

Mitigation methods may be most appropriate for tree species that are both highly selected for by elephants and have poor recruitment rates, which makes the surviving adult trees important seed banks for future generations (for example, *Adansonia digitata* (Venter and Witkowski 2010) and *S. birrea* (Helm and Witkowski 2012)). Managers may also want to protect large trees that provide important nesting sites for birds of conservation concern, such as the white-backed vulture (*Gyps africanus,* Vogel et al. 2014) and the southern ground hornbill (*Bucorvus leadbeateri*, Kemp and Begg 1996). Questionnaire surveys can also be performed to help assess about which trees managers and landowners are most concerned, and where efforts for mitigating purposes should be conducted (Henley 2013).

Conclusion

We have presented the results of field experiments to test the efficacy of four mitigation methods for large tree protection against elephant impact. Whilst disagreement exists over the management strategies surrounding managing elephant impact on large trees, we have provided results on both the effectiveness and logistical constraints of these four mitigation methods to provide conservation mangers with a scientifically assessed 'toolbox'. These tree protection methods should always be viewed as a small-scale solution for protecting large trees from elephant impact, and most applicable to small, protected areas, or where water is readily available to elephants and so elephant impact cannot be managed on a spatial scale (Henley and Cook 2019).

We encourage conservation managers to decide carefully on which methods are both ecologically and economically suited for both their protected areas and their elephant management plans, whilst understanding that method effectiveness may range across various protected areas. These methods can 1) aid in prolonging the survival of large trees in the presence of elephants, 2) protect important habitats of tree-dependent species (Rushworth et al. 2018), 3) ensure that the ecological value of large trees within savanna ecosystems is conserved (Belsky and Canham 1994), 4) ensure that sufficient reproductively adult trees of particular species, is available as potential seedbanks to repopulate the surrounding landscape (Helm et al. 2011), and 5) help reduce disagreements over management decisions related to elephant impact on large trees (Henley and Cook 2019).

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Robin M. Cook: Conceptualization (supporting); Data curation (lead); Formal analysis (lead); Funding acquisition (supporting); Investigation (equal); Methodology (equal); Project administration (supporting); Writing – original draft (lead); Writing – review and editing (supporting). **Edward T. F. Witkowski**: Conceptualization (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Project administration (supporting); Supervision (equal); Writing – review and editing (equal). **Michelle D. Henley**: Conceptualization (lead); Formal analysis (supporting); Funding acquisition (lead); Investigation (supporting); Methodology (equal); Project administration (lead); Resources (lead); Supervision (equal); Writing – review and editing (equal).

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Data availability statement

Data are available from the Dryad Digital Repository: https://doi.org/doi:10.5061/dryad.h18931zsf (Cook et al. 2023b).

Supporting information

The Supporting information associated with this article is available with the online version.

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