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A synthesis of human conflict with an African megaherbivore; the common hippopotamus

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The common hippopotamus is an extant African megaherbivore that is relatively understudied by scientists and underfunded by conservation organisations. Conflict with people, however, is a major concern given the danger that hippos pose to human life. Moreover, very little is known about human–hippo conflict (HHC), and experimental fieldwork on mitigation methods has hardly been conducted. Here we conduct an exhaustive review of the primary and grey literature outlining how the conflict between people and hippos arises, the impacts of conflict on both human communities and hippo populations, and all known intervention measures. Our review highlights the effectiveness of barriers around crops, riparian buffer zones (that exclude cattle and crop planting), and payments for environmental services as tools to mitigate HHC. This study also highlights the knowledge gaps in HHC research, particularly the spatial scale of HHC, the lack of field experimental research on deterrents, and a paucity of knowledge on outcomes of projected climate change and HHC.

KEYWORDS

Africa, hippopotamus, conflict mitigation, human wildlife conflict, freshwater ecology

1 Introduction

The common hippopotamus (*Hippopotamus amphibius*) is a relatively neglected megaherbivore, despite being listed as *Vulnerable* through the International Union for Conservation of Nature (IUCN) Red List (2021). The common hippopotamus (hereafter hippo) is one of two extant hippo species, the other being the pygmy hippopotamus (*Choeropsis liberiensis*). We did not review the pygmy hippos here, as human conflict with these relatively small and forest-dwelling animals is not substantial (IUCN, 2021).

Hippos are among the few extant African megaherbivores, with an adult body mass greater than 1,000 kg (see Owen-Smith, 1988), along with iconic species such as the bush elephants (*Loxodonta africana*). Nevertheless, a simple search of the primary literature through the Web of Science (at March 2022, http://webofknowledge.com) returned ~230 results for *H. amphibius* but ~1,790 for *L. africana*. Hippos may be difficult for scientists to study, given the danger they pose and their nocturnal habits (Eltringham, 1999). The relative neglect of the common hippos in the primary literature may be replicated in conservation funding, with consequences for the persistence of an important megaherbivore.

As with other megaherbivores, hippos have a disproportionate influence on their environment (Cumming, 1982). The nutrient transfer that hippos facilitate, for example, from terrestrial to aquatic systems is substantial; each adult hippo may consume 40-50 kg (wet mass) of forage daily, and most of the hippo excrement is deposited in river systems, amounting to many millions of tonnes annually (McCauley et al., 2015). These nutrient subsidies influence primary and secondary aquatic production and can determine whole-river community composition (Subalusky et al., 2015; Masese et al., 2020). Conversely, where hippo densities are high, such as during dry periods, high nutrient subsidies can quickly lead to water eutrophication and biodiversity loss (Stears et al., 2018).

The wetland trails developed by hippos on their nocturnal forage excursions may, in turn, develop into pools and new river channels, providing new habitat to fish and other aquatic fauna (Bakker et al., 2016). Moreover, the grazing activity of these megaherbivores facilitates "grazing lawns", in turn attracting a diverse grazing herbivore assemblage (Verweij et al., 2006; Kanga et al., 2013) and enhancing spatial vegetation heterogeneity (Lock, 1972). Hippos play a significant role in fluvial geomorphology and nutrient transfer benefits to fish populations (Naiman and Rogers, 1997), which provides an ecosystem service to poor human communities dependent on fish as a source of protein (Mosepele et al., 2009).

Hippos themselves provide a direct ecosystem good, as their meat is valued by people who may consume this legally or illegally (De Boer and Baquete, 1998; White and Belant, 2015). A more formal provisioning service provided by hippos is the monetary gains derived through photographic tourism (Okello et al., 2008) and, to a lesser extent, sport hunting (Kahler and Gore, 2015). Hippos also play an important provisioning service or role in traditional African society, being highly valued for medicine or as part of traditional belief systems (Dossou et al., 2018). In Benin, for example, hippos are valued spiritually as "protectors", which facilitates their conservation (Dossou et al., 2018). In South Africa, hippos are valued greatly by traditional healers who use their body parts as medicine (Green et al., 2022).

The life history, behaviour, and genetic structure of the common hippos are adequately detailed elsewhere (see Smuts and Whyte, 1981; Owen-Smith, 1988; Eltringham, 1999; Stoffel et al., 2015). Hippos are large-bodied and long-lived, with sexual maturity typically attained after 5 years, and their gestation length is long, as are inter-calving periods (Smuts and Whyte, 1981). Hippos have well-developed senses, although their eyesight may be relatively weak (Eltringham, 1999). Both adult male and female hippos weigh over 1,000 kg, and there is sexual dimorphism (Owen-Smith, 1988). Megafauna like hippos may be vulnerable (to extirpation), as body mass is a known extinction correlate among vertebrates, in particular tropical mammals (Fritz et al., 2009). Through allometry, body mass determines "the intrinsic rate of natural increase" or r_{max} (Fenchel, 1974), and extinction risk is inversely associated with r_{max} (Hutchings et al., 2012). Hippo populations are thus slow to respond to high rates of offtake, such as illegal killing, and may quickly become locally extinct. Threats to hippos may vary across regions, but in the present Anthropocene, hippos have been reduced to a fraction of their former range through retributive killing (Ripple et al., 2015), habitat loss, and over-hunting for their meat, hides, and ivory (Nielsen and Meilby, 2015; Scholte and Iyah, 2016). Hippos are vulnerable to killing by people, as they are predictable in their use of trails out of the water, allowing for the setting of pit traps (Walker, 1967). Moreover, they may be restricted to pools of water during the daytime and present a target for people in possession of firearms. Hippos are also negatively affected by upstream dams and irrigation schemes that alter river water flow (Smuts and Whyte, 1981).

Hippos have small home ranges (mean of ~8 km^2) relative to other large herbivores, and adult males have been recorded to move ~15 km upstream over dry periods (Stears et al., 2019). (Owen-Smith 1988) estimated that adult hippos will forage as far as 10 km away from water, again during the dry season. These excursions away from water invariably bring hippos into direct conflict with people (Kendall, 2011) because hippos may raid crops (De Boer and Baquete, 1998) or because they harm or kill people who encounter them on land (Dunham et al., 2010).

Human fatalities from hippo attacks may not be as high as those from elephants (see data in Dunham et al., 2010); nonetheless, hippos do kill many people in Africa (Durrheim and Leggat, 1999; Post, 2000). Likewise, conflict with people results in the substantial retributive killing of hippos (Dunham et al., 2010). Certainly, human–hippo conflict (hereafter HHC) is a concern to African conservation scientists who want to reduce human injury and fatality and conserve an important megaherbivore. Nevertheless, no detailed review of HHC and the mechanisms to mitigate this has been produced in the primary literature. There have been a number of useful studies on HHC, but these have been site- or region-specific (Mkanda, 1994; Dunham et al., 2010; Kendall, 2011; Utete, 2020).

Here we provide an Africa-wide synthesis of the literature on HHC. We used the Web of Science (https://webofscience.com) and Google Scholar (https://scholar.google.com) to access articles published on the common hippopotamus in the primary and grey literature. Our search terms and a spreadsheet of the sourced references are in the Supplementary Material. Our review provides practical advice on conflict mitigation that may be useful to conservation practitioners. Moreover, we highlight gaps in knowledge, thereby facilitating future multi-disciplinary research on an important megaherbivore.

2 Human–wildlife conflict

First, we provide background on human–wildlife conflict (hereafter HWC), which HHC falls under. According to the IUCN Human-Wildlife Conflict Task Force (http://hwctf.org), "HWC arises when animals pose a direct threat to the livelihood or safety of people and this results in persecution of that species." Within the primary literature, HWC is "the situation that arises when behaviour of a non-pest, wild animal species poses a direct and recurring threat to the livelihood or safety of a person or a community and, in response, persecution of the species ensues" (Inskip and Zimmermann, 2009).

HWC is by no means a novel challenge. The evolution of our own species is partly a story of HWC given that African hominids were required to adapt to an environment in which large animals posed a direct threat (Rose and Marshall, 1996; Lee-Thorp et al., 2000). In the present Anthropocene, however, wild animal species may lack the capacity to adapt to human persecution (Vermeij, 2012), so HWC is now a leading conservation concern. In sub-Saharan Africa, persecution may principally be illegal hunting, such as for bushmeat as well as retributive killing following conflict (Ripple et al., 2015). These factors act additively with habitat loss and are as urgent as climate change (Caro et al., 2022).

Body size is a fairly robust predictor of HWC, as large-bodied vertebrates are more likely to injure or kill people, raid crops, or kill livestock (Inskip and Zimmermann, 2009; Nyhus, 2016). Equally, the retributive killing of wildlife is more likely to target large animals that are relatively easy to track and sight. Many of the animals repeatedly identified as leading causes of conflict, such as lions (*Panthera leo*), elephants, cape buffaloes (*Syncerus caffer*), and hippos (Newmark et al., 1994; Mukeka et al., 2020), are also "charismatic fauna" that receive substantial conservation and public attention. African communities living alongside these animals incur the costs of conservation through crop damage and livestock loss but may see little benefit through ecotourism (West et al., 2006). The financial costs of HWC imposed on rural people can be very high (Sitienei et al., 2014). For example, livestock depredation (by large predators) affected ~18% of African households and disproportionately affected low-income rural people, with up to 50% per capita income loss (Dunnink et al., 2020).

The impacts of HWC on communities go further than the loss of crops/livestock. More indirect effects include the opportunity costs imposed on communities when adults must guard crops and are not employed elsewhere (Barua et al., 2013). Further, children may miss school, or underperform at school, when they are needed to guard crops (Mackenzie and Ahabyona, 2012). There are also negative mental health effects where communities witness human fatality through conflict with wildlife and the loss of income when breadwinners are killed (Dickman et al., 2011).

2.1 Conflict mitigation

Several approaches may mitigate HWC that broadly fall under direct or indirect interventions (see Treves et al., 2009). Direct mitigation includes 1) culling or lethal removal of problem animals, as well as non-lethal approaches such as translocation or sterilisation; 2) physical barriers, such as fences (including electric fences), trenches, and buffer zones; and 3) chemical-, light-, or audio-based repellents and guarding strategies. Indirect interventions include 4) compensation and incentive schemes and 5) co-management of resources and community-based conservation schemes, including legal processes that devolve ownership of wildlife to landowners or communities (Taylor, 2009; Treves et al., 2009; Hoare, 2015).

While much is now known about the mitigation of conflict, there has been criticism of "win–win" conservation initiatives that more commonly fail than succeed (McShane et al., 2011). Compensation for wildlife damage, for example, may become a form of agricultural subsidy that, in turn, triggers agricultural expansion and subsequent habitat loss (Bulte and Rondeau, 2005). A "moral hazard" may also occur when communities fail to protect livestock or crops in order to then claim compensation (Dickman et al., 2011).

There is recent recognition that HWC may, in some regions, be a proxy for human–human conflict (Madden and McQuinn, 2014). Deep-rooted and underlying conflict, for example, would include a situation where HWC has been ongoing and little has been done to address the needs or concerns of communities, with a subsequent breakdown of trust (Zimmermann et al., 2020). Thus, the mitigation of HWC may need to include empowering and restoring dignity to affected human communities.

3 Human–hippo conflict

We adopt a formal definition of HWC (see Inskip and Zimmermann, 2009) and stipulate that HHC arises "when hippo populations pose a threat to human lives or livelihoods, which may in turn result in the retributive persecution of the animals." Proximity to water underscores all HHC in Africa, with most conflict taking place within 1,000 meters away from water (Post, 2017). HHC principally occurs where people practice subsistence-level farming and fishing, but tourist operators with lodges near watercourses also encounter conflict with hippos (Durrheim and Leggat, 1999), as do commercial large-scale croppers and pastoralists (Seoraj-Pillai and Pillay, 2017). Much of the subsistence farming in sub-Saharan Africa is rain-fed and not irrigated, and this may motivate people to farm near water sources, thereby exacerbating conflict (Utete, 2020; Marowa et al., 2021).

HHC manifests as loss of human life and injury, loss of human livelihood and welfare, crop and livestock loss, competition for forage with livestock, damage to fishing gear and boats, and retributive killing of hippos (Anderson and Pariela, 2005; Post, 2017). In Kenya, HHC incidents increased by 1285% from 1997 to 2008 (Kanga et al., 2012). Clearly, HHC is a leading driver of hippo extirpation, and this may worsen as human populations grow (Bradshaw and Di Minin, 2019).

3.1 Human injury and fatality through human–hippo conflict

On land, it appears that many incidents are accidental, where people encounter hippos, and the animals then attack (Anderson and Pariela, 2005). Hippo may, however, be provoked into an attack when people attempt to drive them from crops (Post, 2017). Medical specialists recommend that hippo-inflicted injuries be considered a special group of animal attacks, classified as "major trauma, rather than mammalian bites" (Haddara et al., 2020). Hippos may trample people, but much of the trauma of an attack appears to be through bites. Indeed, the bite force of the common hippo is 12,600 kPa, relative to that of a lion at 4,500 kPa (Haddara et al., 2020).

A well-cited statistic states that "More people are killed by hippopotamuses than by any other African animal" (Kendall, 2011), but very few data support this notion. Indeed, data published on human fatality in Africa through HWC show that bush elephants are responsible for more human deaths than hippos (Dunham et al., 2010; Kahler and Gore, 2015). Of interest though are data presented in a paper on human evolution (see Treves and Naughton-Treves, 1999) that showed that of all attacks on people, *proportionally* more people died from hippo attacks than from any other large animal, including lions. The authors used archived HWC data from the Ugandan Game Department (1923–1994) and showed that of all attacks on people by elephants, (human) fatality was 67%; of all attacks on people by lions, (human) fatality was 75%; and of all incidents of attacks on people by hippos, (human) fatality was 87% (Treves and Naughton-Treves, 1999). Conversely, data on HWC from Mozambique (Dunham et al., 2010) showed that human mortality was proportionally higher when attacked by elephants (84%) or crocodiles (*Crocodylus niloticus*) at 79% than attacks by hippos (55%). Thus, while it may not be entirely factual to say that "hippo kill more people than any other animal in Africa", it is true that when hippo attacks do occur, the likelihood of (human) death is high to very high. Further, where people do survive hippo attacks, it is probable that the victims will suffer amputation and/or permanent disability (Haddara et al., 2020).

Human injury at the water's edge or in the water is by no means uncommon (Marowa et al., 2021). Hippos may be provoked to attack if they get caught in nets, and hippos will attack canoes or small boats (Dunham et al., 2010). Fishing communities may also place fish traps at hippo slipways, increasing the chance of surprising hippos and precipitating an attack (Post, 2017). The demography of human victims of hippo attacks may be skewed towards young adult men. An article on hippo bite morbidity (Haddara et al., 2020) mentions injuries presented by 11 patients, of whom nine were men (82%) and two were women (18%), and the mean patient age of 31. In Uganda, young men (active in fishing) were more exposed to wildlife-associated injury (Kabuusu et al., 2018). Traditional roles in rural settings may determine the age and gender of human casualties through hippo attacks (Post, 2017).

3.2 Human trauma, mental health, and other hidden costs

Human welfare and mental wellbeing are likely affected by HWC (Barua et al., 2013). Damage to boats by hippos, for example, may have a considerable financial impact on people who are already economically marginalised (Marowa et al., 2021). The toll on spouses and children who witness the death of a relative may be substantial. In India, for example, the death of a family member following a wildlife conflict resulted in a high likelihood of post-traumatic stress disorder, childhood emotional disorder, and clinical depression among those left behind (Barua et al., 2013). If the person killed through wildlife conflict was a breadwinner or principal carer, then there may be an increase in family debt and disruption to child–parent bonding (Jadhav and Barua, 2012). Moreover, where people do survive hippo attacks, the injuries are so traumatic that the victim will likely be disabled after the event (Haddara et al., 2020) and will therefore be unable to be fully effective as a carer or breadwinner. We cite case studies in Asia here, but the mental health outcomes of human–wildlife conflict will be similar with those in Africa.

3.3 Crop damage, grazing competition, and loss of livestock

Other than human injury or fatality, loss of crops to hippo foraging activity is a leading cause of HHC (Kendall, 2011; González et al., 2017). Crop damage is an often cited reason for the negative perception that African communities have of hippos (De Boer and Baquete, 1998; Gandiwa et al., 2013), and of the reports made to authorities on HHC in Kenya, the majority (>70%) of those are related to crop damage (Post, 2017).

Crop raiding by hippos occurs mostly at night (Kendall, 2011). Crops and vegetables are mostly fed on but may also be damaged by trampling. The closer the crops and vegetables to water bodies and hippo access points, the higher the likelihood of raids (Kendall, 2011; Post, 2017). Crop raiding often arises in floodplains that hippos may have used in the past and have subsequently been converted to crops, such as rice (Kuye et al., 2021). Crop raiding by hippos may be seasonal too, affected by rainfall and crop growth stages (Kendall, 2011; Post, 2017). Food and cash crops damaged by hippos include maize, rice, pumpkins, groundnuts, sweet potatoes, cassava, sugarcane, sorghum, wimbi, cabbage, and cowpeas (Clarke, 1953; Post, 2017; Gross et al., 2018). In 2008 in the Lake Victoria region of Kenya, crop damage to 326 small farms totalled ~52,000 USD, which when averaged per farm was greater than the monthly household income (Post, 2017). In Namibia in 2009, crop damage by hippos was estimated at 2,193 USD per hectare (Kahler and Gore, 2015). The same study found that the costs of crop damage (by hippos) were greater than the income generated by the species (through tourism and hunting), while the opposite was true of elephants (Kahler and Gore, 2015).

Hippos are principally grazing herbivores, which may lead to competition with livestock that requires access to the same forage (Kanga et al., 2013). In the West African state of Guinea, conflict with livestock was identified as a key threat to hippos (Brugiere et al., 2006). The depletion of natural forage by livestock will also drive hippos to raid crops, which then drives conflict with people (Post, 2017). Villagers in Kenya reported that hippos maimed or killed cattle, sheep, and goats (Post, 2017), and hippos have been blamed for disease outbreaks (Kahler and Gore, 2015).

3.4 Hippo mortality and injury through conflict

The retributive killing of hippos (by people) because of conflict may be substantial. The ratio of hippos killed for every human casualty may be higher than for other species; in Mozambique, there were 2.7:1 hippos killed relative to human loss, 2.3:1 for bush elephants, 1.4:1 for buffaloes, and 0.6:1 for lions (Dunham et al., 2010).

Authorities may further shoot hippos in response to crop raiding or other reports of conflict, although this is more *ad hoc* control than culling (Mkanda, 1994). The Kenya Wildlife Service has regularly killed hippos, in response to serious conflict between villagers and hippos (Post, 2000), and in Mozambique, ~60 hippos were killed over a 2-year period in direct response to conflict with people (Dunham et al., 2010). Around Lake Kariba in Zimbabwe, villagers complained that authorities did not kill *enough* problem hippos and stated that park rangers will simply shoot over the animals' heads to deter them (Marowa et al., 2021). There has been some concern that conflict with hippo may be exaggerated; a government authority in Uganda commented that the hippos "owing to the attention attracted by its bulk, continues to enjoy an undeserved reputation for ferocity coupled with that of a perpetrator of excessive damage" (Uganda Game Dept Report in Clarke, 1953).

Data on hippo injury through conflict are not widely available. Mkanda (1994) recorded 928 hippos killed and 651 wounded by the Game Department in Malawi from 1984 to 1989. Wounded hippos may succumb to their injuries later or may become aggressive and pose a danger to human life, which exacerbates conflict. Clarke (1953) further noted that villagers shot at hippos with inadequate weapons (such as shotguns), which only then enraged the animals. Of note, Post (2017) recorded the poisoning of hippos by villagers affected by raiding of crops; affected communities used the insecticide *carbofuran* (known commercially as *Furadan* in East Africa). Poisoning is a conservation concern beyond just hippos, as high mortality rates have been recorded in vultures that have fed on poisoned carcasses (Ogada et al., 2016).

4 Mitigation of human–hippo conflict

We note a relative paucity of literature pertaining to the mitigation of HHC. Very little experimental work has been done to test the behavioural response of hippo to deterrents, for example.

4.1 Direct methods

These include physical mitigation approaches such as lethal and non-lethal control and habitat manipulation (see Nyhus, 2016).

4.1.1 Lethal removal

The most apparent means to deter hippo conflict is the lethal control of the animals, be this at an individual or population level (see Table 1A). Lethal control principally implies the shooting of the animals, but sometimes villagers will poison hippos. Even where authorities shoot offending hippos, the approach does not stop conflict (Mkanda, 1994), and injured hippos will pose an even greater danger (Clarke, 1953).

4.1.2 Non-lethal removal

This includes translocation (Lekolool, 2012), although the process is expensive (Kanga et al., 2012), and hippos are dangerous. Moving animals to a new site is only recommended where other options have failed or the remaining animals have little chance of survival (Anderson and Pariela, 2005). Translocations of hippo populations in southern Africa have failed where habitat suitability assessments were inadequate (Novellie and Knight, 1994). Sterilisation has been

TABLE 1A Direct intervention measures used to mitigate HHC, structured after Treves et al. (2009).

Direct intervention	Example	Explanation	Considerations	References
Population manipulation	Lethal removal	Animals are killed following a serious incident (human injury or mortality) or as population control. Typically conducted by wildlife professionals. Meat may be provided to communities.	Lethal removal may appease communities, and deal with dangerous individual animals, but it does not solve the conflict in the long term. Injured animals may pose further danger. Culling may attract negative media attention.	(Mkanda, 1994; Dunham et al., 2010; Post, 2017)
	Non-lethal removal	Removal or translocation. Typically involves the use of capture bomas or sedation. Sterilisation has been attempted	Animals are dangerous and challenging to immobilise. The process can be costly and requires a full habitat assessment of the new site; otherwise, it is likely to fail.	(Novellie and Knight, 1994; Kanga et al., 2012; Lekolool, 2012)
Barriers	Fences and ditches	Includes electric fences or even low-lying cables as hippo cannot step over cable ~80cm above the ground. Also includes pole barriers and thorn or even sisal barriers. Ditches of ~1.8m deep appear to deter hippo. Stone walls also work.	Hippo may habituate and learn how to get through fences. Wire cabling for electric fences may be used to snare animals. Electric fences are costly and difficult to maintain. Sisal or thorn barriers take time. Sisal is non-native. Ditches require substantial labour and may inadvertently become pit traps to smaller animals.	(Clarke, 1953; Lock, 1972; Anderson and Pariela, 2005; González et al., 2017; Post, 2017)
Repellents and deterrents	Acoustic	Includes audio playback, sound machines, drumming and shouting.	Playback systems may be costly, and animals may habituate to the noise. Drumming and shouting requires people to watch over fields at night.	(Post, 2017; Dossou et al., 2019)
	Light based	Includes lighting systems near crops and basic sources of light like torches and bonfires. Strobe lights have successfully deterred elephant.	Fires can consume a lot of fuel. Little experimental work has been done on automated lighting. Hippo may habituate to light.	(Post, 2017; Dossou et al., 2019; Adams et al., 2021)
	Chemical	Very little is known about chemical repellents. Anecdotal evidence of pesticide or other smeared on crops to deter grazing. no work on olfactory deterrents.	Little is known. Success of chilli-based deterrents on elephant may not work with hippo.	(Post, 2017)
	Guarding, other	In combination with sound and visual deterrents (fires), human presence has some success. Scarecrows have been used.	Guarding is a high risk to people and results in lost days at school or work. When scared by people, hippo will trample crops and do more damage than if not disturbed.	(Post, 2017; Dossou et al., 2019; Gross et al., 2019)
Habitat manipulation	Riparian buffer zones, corridors	Buffer zones enable hippo grazing and mitigate competition with livestock. Should extend at least 2km from water – preferably up to 10km. Corridors allow for dispersal. Past work on protected zones for hippo show success.	Provides important protection to hippo (the species is protected – but their habitat is not). Conflict arises when people infringe on buffer zones – so success depends on zones being acceptable to communities.	(Sheppard et al., 2010; Perry, 2015; Post, 2017; Dossou et al., 2019; Stears et al., 2019)

Papers cited in the Table are provided in the reference list.

implemented to control hippo populations in South America (Colombia), where the species is non-native and has now established a wild population (Castelblanco-Martínez et al., 2021). Sterilisation may not be effective in Africa, given the costs of implementation and the likelihood that incoming non-sterilised individual animals may be the source of a new population.

Note here that our study explicitly addresses the conflict between the common hippos and people in Africa, but the introduced population of hippos in Colombia does provide an interesting case study. A key dilemma for South American conservationists is whether to remove all hippos or allow the animals to range freely and fill a niche that was lost following the Pleistocene extinction event (Dembitzer, 2017; Shurin et al., 2020).

4.1.3 Fences and trenches

These are other forms of direct physical intervention. These may deter hippos from crop raiding or may even be used to restrict grazing by hippos in areas set aside for livestock. Perhaps the most effective of all deterrents is a low-lying (~75 cm above ground) strong rope or steel cable, as hippos cannot step over this (Clarke, 1953; González et al., 2017). The stakes or pickets holding the cable will need to be very strong, as there is anecdotal evidence that hippos will lean on fences to push these over (Post, 2017). Electric fences (where cabling runs ~80 cm above ground) may be effective at keeping hippos away from crops, as the species' nasal area is sensitive (González et al., 2017). Electric fences, however, can be costly and difficult to maintain. Moreover, the wiring may be appropriated and used to construct snares. Other effective barriers include stone walls

(Post, 2017), thorn bush bomas, and sisal fences (Anderson and Pariela, 2005). Sisal (*Agave sisalana*) are non-native plants, and sisal fences will take time to become established.

Trenches will deter hippos, and it seems that trenches need to be fairly deep, as much as 1.8 m (Lock, 1972). It also appears that ditches, coupled with fences, may be effective (Lock, 1972), and fences need to be robust in structure (see field images in Post, 2017).

4.1.4 Repellents

These include acoustic, olfactory, biological, or visual repellents or deterrents. Light-based deterrents include the lighting of bonfires and torches (Dossou et al., 2019), although these require people to remain near fields. The response of hippos to permanent lighting near fields, such as solar-powered strobe lights (see Adams et al., 2021), is unknown. The animals may habituate to lighting placed near fields.

Acoustic deterrents may include shouting and the banging of drums or bells (Post, 2017), although, again, these necessitate human presence in fields. Sirens or hooters will deter hippos (Post, 2017), but they may habituate to these. The response of hippos to audio playbacks, such as felid growls (see Thuppil and Coss, 2016), is not documented. Bear Bangers may also deter hippos, although these could provoke the animals into an attack.

Olfactory deterrents may be natural or synthetic. Much is known about the use of chili pepper to deter elephants, for example (Montgomery et al., 2021), although hippos may be less sensitive to peppers. Elephants also show aversion to olfactory predator signals (Valenta et al., 2021), and it is likely that hippos, too, would show aversion to these. Again, it appears that little experimental work has been documented. There is anecdotal evidence that farmers smeared (unknown) substances onto the leaves of crops favoured by raiding hippos (Post, 2017) and that this method works. There is potential for aromatic plants to be mixed with crops to deter hippo grazing (for example Gross et al., 2017), and this requires further investigation.

More generally, beehives and the audio playback of agitated bees have helped to mitigate human–elephant conflict (Hoare, 2015), with no apparent success in deterring hippos. Naturally, elephants may be physiologically more sensitive to bee stings. Scarecrows have successfully kept hippos away from fields and paddocks in East Africa (Post, 2017), and propane cannons (used to scare birds) may work.

4.1.5 Protected zones or riparian buffers

Hippos may be protected by law, but their habitat is not (Mackie et al., 2013), so riparian buffers not only mitigate against conflict but also help conserve hippos by providing for vital grazing areas. Moreover, almost all conflicts between people and hippos occur close to water (Post, 2017; Dossou et al., 2019), so protected zones that exclude people and livestock will mitigate most conflict. Competition for grazing between hippos and livestock is a source of conflict that may be overlooked.

Hippos tend not to move far from water while foraging at night. On average, animals will forage from 0.6 to 1.7 km away from water (O'Connor and Campbell, 1986), with a recorded maximum distance of 4.7 km away from water (Stears et al., 2019) and an estimated maximum distance of as much as 10 km (Owen-Smith, 1988). Thus, buffers need to run parallel to watercourses and stretch perpendicular to watercourses by at least 2 km, but preferably 5–10 km from the water.

Outside of protected areas, it does seem that the establishment of protected riparian zones is best done *via* community-based conservation. One precedent is the Wechiau Community Hippo Sanctuary in Ghana (Sheppard et al., 2010). The sanctuary set aside a core riparian zone (2 km) where hippos were permitted to graze un-interfered and a development zone (5–10 km), which allowed a sustainable use of resources. Income was generated through ecotourism (Sheppard et al., 2010), the hippo population remained stable, and biodiversity increased. In some regions, however, the costs of hippo crop damage may outweigh the benefits incurred through tourism or sport hunting (Kahler and Gore, 2015).

Riparian buffer zones appear to be one of the more effective practical approaches to mitigate conflict between hippos and human communities. Extensive buffer zones may also act as corridors, allowing for the dispersal of animals between sub-populations (see Stears et al., 2019).

4.2 Indirect methods

These may include incentives that encourage coexistence with hippos, such as compensation or even devolution of ownership to local communities. Indirect methods may further include education on the benefits of hippo conservation or even punitive schemes designed to discourage the killing of animals (see Table 1B).

4.2.1 Compensation

Reimbursement for the loss of crops or livestock, or even human injury or fatality, is the most obvious financial incentive scheme. It does seem, however, that compensation varies by country, and in some states, barely exists at all. In Namibia, the government may not be held responsible for human injury or fatality but will cover only basic costs such as funeral expenses (MET, 2009). In Kenya, the government will compensate communities for death or injury following a conflict, but not for the loss of crops or livestock (Post, 2017), and a survey of communities near Kariba in Zimbabwe found that villagers received no compensation following HWC (Marowa et al., 2021). Compensation for crop damage also varies and in many instances does not occur, or villagers themselves may not even be aware that they can claim damages (Post, 2017). In Namibia, for example, the State will compensate farmers for the loss of crops

TABLE 1B Indirect intervention measures used to mitigate HHC.

Indirect intervention	Example	Explanation	Considerations	References
Compensatory schemes	Direct compensation	Compensation usually follows human casualty or crop damage. Laws vary across African countries. Typically, compensation is less than the value of loss. Many wildlife authorities do not compensate for crop damage.	Paperwork discourages many communities. Compensation schemes may facilitate corruption or fraudulent claims and may end up subsidising agriculture. Alternatives, such as training in mitigation approaches, are often encouraged.	(Lamarque et al., 2009; Dunham et al., 2010; González et al., 2017; Post, 2017; WWF, 2020)
	Conservation payments	Includes compensation to encourage coexistence and payment for ecosystem services. Payments are linked to the desired outcome, such as the presence of hippos.	Little work done on payment for hippo ecosystem services. Payments to encourage coexistence to appear better able to provide long-term solutions. May act as a "welfare magnet".	(Dickman et al., 2011)
Revenue sharing	Income generation and distribution through sustainable use	Includes income derived from tourism and sport hunting as well as meat provision and sales. Much of this is linked to community-based conservation and private conservation. Rationale is that if the benefits accrued by sustainability outweigh the costs of living with hippos, people will tolerate them.	While there are clear examples of successful conservation initiatives where tourism and hunting have provided income, there are some failed initiatives too. There is further opportunity for elite capture and unethical or unsustainable practice.	(Okello et al., 2008; Dickman et al., 2011; White and Belant, 2015; Scholte et al., 2017; Utete, 2020)
Legal interventions	Devolution	A legal process that passes decision making onto communities. Some precedent in southern Africa where income can be derived from wildlife through tourism and/or sport hunting. Provides for local empowerment.	Devolution does go some way to recognising that human–wildlife conflict is often a continuation of human–human conflict over resource access. The process may rely on conservation aid. Elite capture and corruption may occur.	(MET, 2009; Taylor, 2009; Sheppard et al., 2010; Post, 2017)
	Law changes	Hippos are listed under CITES (Appendix II), and the species have partial or full protection in most states where they occur. Law enforcement varies by state, and studies show that most communities are not aware of laws around problem animal control.	Local changes in laws to protect hippos from retributive killing may not be necessary, as their legal status is clear. Enforcement is lacking, and communities need to be aware of legal protections and their rights. Some states lack legal frameworks and policies on dealing with conflict.	(De Boer and Baquete, 1998; Anderson and Pariela, 2005; Lamarque et al., 2009; Sheppard et al., 2010)
Education	Outreach and school-level education	Includes alerting communities to all legal rights afforded to both hippos and themselves. Education may also target communities and school children, alerting them to the benefits of wild animals such as hippos (ecosystem services).	Few studies on this topic. Work in Ghana showed school children were supportive of hippo conservation. Study in Zimbabwe showed outreach did little to change perception of hippos as a problem animal.	(Sheppard et al., 2010; Gandiwa et al., 2013)

HHC, human–hippo conflict.

to hippos and elephants only (MET, 2009), while in South Africa, communities are compensated for livestock loss only, not crop damage (WWF, 2020). In Ghana, compensation for crop loss is not permitted, but rather assistance is provided to prevent further crop damage (Lamarque et al., 2009), and in Mozambique, no compensation is paid for crop loss (Dunham et al., 2010). Indeed, it has been indicated that the Mozambican Government simply cannot afford compensation (Anderson and Pariela, 2005).

While cash payments may go some way towards encouraging the coexistence of people with wildlife, there are substantial challenges posed. For example, compensation schemes may be undermined by fraudulent claims, theft of funds by officials, and bureaucratic ineptitude (Lamarque et al., 2009). There may also be a lack of human capital required to facilitate transparent compensation schemes. In Namibia, Ministry of Environment and Tourism staff are required on the ground to verify crop or livestock damage (MET, 2009), and Namibia may have the funds required to support field staff. However, it appears that Mozambique cannot support such full-time staff (Anderson and Pariela, 2005), and villagers in Zimbabwe complained that National Parks staff did not take reports regarding HHC seriously (Marowa et al., 2021). Likewise, Zimbabwe National Parks staff themselves indicated that they lacked the resources required to attend to all complaints of conflict (Marowa et al., 2021).

Further challenges around compensation schemes are that these may dissuade people from protecting their crops and may even act as a form of subsidy that encourages agricultural expansion, which in turn exacerbates conflict (Bulte and Rondeau, 2005). Compensation is also typically below the market value of the crop or livestock loss and does not protect vulnerable people from further loss (Kahler and Gore, 2015).

4.2.2 Conservation payments

These are payments linked directly to the desired conservation outcome (Dickman et al., 2011), which here may be the persistence of hippo sub-populations. Such payments may not directly attempt to mitigate conflict but do attempt to encourage conservation. Communities living alongside hippo populations would, for example, be compensated for the continued existence of those hippos based on, for instance, annual counts. Payments to encourage coexistence do not necessarily exclude rural people from using natural resources, as protected areas may. Conservation payments can, however, act as a "welfare magnet" (Zabel and Holm-Muller, 2008) and may facilitate elite capture, and distortion of key metrics may occur (see Dickman et al., 2011). Notably, "land rent" paid to communities living alongside hippos in Zimbabwe has been encouraged (Utete, 2020).

One payment scheme that has not been widely trialed with hippos is payment for ecosystem services (PES). Hippos provide substantial ecosystem service to freshwater systems (Mosepele et al., 2009), and formal payments towards communities that live alongside hippos may encourage coexistence.

4.2.3 Revenue sharing

This includes income generated from photographic tourism or sport hunting that goes back to communities, typically through community-based conservation. Hippo meat has been provided to rural people in Zambia (White and Belant, 2015), and the contribution of hunting to the conservation of hippos has been noted elsewhere (Scholte et al., 2017). Photographic tourists want to see hippos (Okello et al., 2008), and the income generated by tourism has supported hippo conservation (Sheppard et al., 2010).

4.2.4 Devolution

The devolution of decision making in natural resource management can mitigate conflict by empowering the very people affected (Taylor, 2009). Communities may decide to derive income through photographic tourism or hunting and may cull hippos for meat. In some parts of Zimbabwe, community conservation has not necessarily led to positive conservation outcomes for hippos (Utete, 2020), although this may be through elite capture (Gandiwa et al., 2013). The transfer of decision making around problem animal control (to local communities) and conservation awareness and education programmes may minimise hippo–human conflict in Zimbabwe (Gandiwa et al., 2013).

4.2.5 Education

Remarkably, there are very few papers that mention the success of education programmes to mitigate HHC. In Zimbabwe, conservation awareness programmes did not appear to change perceptions towards hippos (Gandiwa et al., 2013), although villagers' attitudes towards lions did change. In Ghana, children living close to conservation areas that attracted tourists were more likely to be aware of conservation benefits than children in relatively isolated areas (Sheppard et al., 2010). Conservation outreach and awareness programmes are not uncommon in areas where hippos occur, likely influencing attitudes. More needs to be done around conservation awareness as a means of mitigating conflict (Gandiwa et al., 2013).

We have detailed both direct and indirect approaches to potentially mitigate conflict here, but naturally, these may be more effective when used together or as required by the context within which conflict occurs. We have also provided reference to subsistence farming here, as this is common across Africa. Commercial croppers and pastoralists may also come into conflict with hippos, and more direct approaches such as fences will be appropriate, as well as income generation through tourism and sport hunting.

5 Discussion

The conflict between human and hippo populations will not end in the foreseeable future and indeed may worsen with a projected increase in anthropogenic impacts (Bradshaw and Di Minin, 2019). This paper provides useful information to conservation decision makers and highlights the obvious gaps in knowledge around HHC.

Looking forward, there is an opportunity to expand community-based hippo conservation schemes across Africa, based on Ghana's Wechiau Community Hippo Sanctuary (Sheppard et al., 2010). Southern Africa has led the way in community-based conservation (Taylor, 2009), and that expertise could be used to set up riverine buffer zone sanctuaries in communal lands, where people benefit from all funds generated. Funding options could be extended beyond ecotourism and sport hunting to include formal PES schemes, for example.

Future field research could focus on experimental trials of deterrents and how hippos respond to these. This has been done for other megaherbivores, for example (Montgomery et al., 2021), but little has been done for hippos. It may be that simple methods, such as trenches or robust barriers around crops and villages are the most effective mitigation approaches. Nonetheless, there is an opportunity to test hippo response to olfactory, visual, and acoustic deterrents, for example, and how these may be used additively with other mitigation approaches.

Further research may explore the role that hippos play in disease transfer to cattle, and the spatial aspect of HHC should be documented. This may include the identification of hotspots of conflict. Leading on from this, there is a need to simulate outcomes for hippo populations under climate change. Changes to rainfall patterns will vary greatly across Africa under climate change, with projected increases in annual rainfall in some regions and decreases in others (Scholes et al., 2015). River flows will likely be affected by changes across their entire catchment (Falloon and Betts, 2006), and thus outcomes may vary for hippo populations.

Following on, there is a need for ecologists to work with anthropologists, social scientists, and health specialists. The impacts of HHC on communities require further work, in particular, the likelihood that young breadwinners may be disproportionately injured or killed through conflict. Work also remains to be done too on human mental health outcomes from HHC, as has been done around human–elephant conflict in Asia (Jadhav and Barua, 2012). Further, there is much opportunity for scientists to better understand and document African perspectives on hippos. This includes documentation of the cultural values that African societies attribute to hippos, such as has been done in Benin (Dossou et al., 2018). A common problem of conservation in sub-Saharan Africa is the perception that the movement is centred on Western value systems, and not enough is done to incorporate local concerns and culture (Cocks et al., 2012; Sibanda, 2015). An understanding of how hippos are perceived and valued by Africans will facilitate culturally sensitive policy (for example Goldman et al., 2013).

Finally, education and outreach programmes have a role to play in informing people about the great cultural value that hippos may have to African communities, as well as the role that hippos play as ecosystem engineers and tourist attractions. If outreach programmes emphasise to rural poor people that hippos have cultural value, as well as ecological and economic values, then they may perceive that the benefits of keeping hippos can outweigh the costs, and the animals may be tolerated. Scientists too may play a role in informing a global audience on the ecological, evolutionary, and cultural significance of this quaint and overlooked species.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Conflict of interest

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

Publisher's note

Supplementary Material

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