Title: Fencing Africa's protected areas: costs, benefits, and management issues

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ABSTRACT

The fencing of protected areas (PAs) is highly controversial, and much remains unknown about the associated financial, ecological, and social impacts. We surveyed experts on 63 fenced and 121 unfenced PAs across 23 African countries to assess the advantages and drawbacks of fencing. Where fences exist, they are largely supported and widely viewed as effective at demarcating PA boundaries and mitigating human-wildlife conflicts. However, most fences were insufficiently funded, which limited their ability to contain conflict-prone species like elephants and lions. Fences were also frequently vandalised and caused numerous conflicts with local communities. We documented for the first time the distribution of and support for fencing in PAs

across Africa. While fencing is largely limited to Southern Africa and East Africa, support for fencing is greatest in West Africa and is associated with high human and livestock densities, and high threats from bushmeat harvesting, livestock encroachment, and logging.

INTRODUCTION

The use of fencing in Africa's protected areas (PAs) has sparked considerable discussion and debate in recent years (Ferguson & Hanks 2010; Somers & Hayward 2012; Packer *et al.* 2013a; Creel *et al.* 2013; Packer *et al.* 2013b; Woodroffe *et al.* 2014; Durant *et al.* 2015). Under certain circumstances, fences have the potential to provide significant benefits for both people and wildlife. Appropriately planned, designed, and maintained fences can mitigate human-wildlife conflicts precipitated by wild animals raiding crops, depredating livestock, and attacking people (Kioko *et al.* 2008; Sapkota *et al.* 2014; Miller *et al.* 2016), and thus play an important role in the conservation of large herbivores and carnivores (Ripple *et al.* 2014; Ripple *et al.* 2015; Trinkel *et al.* 2017). Fences can also reduce encroachment and poaching for bushmeat and other wildlife products (Hayward & Kerley 2009; Hayward 2012; Somers *et al.* 2012), which helps to maintain biodiversity within PAs (Massey *et al.* 2014).

However, fences often have unintended ecological and social consequences. From an ecological perspective, fences can interfere with wildlife migrations and dispersals (Cushman *et al.* 2016), which can contribute to significant die-offs of ungulates and other animals when resources become locally scarce (Williamson & Mbano 1998; Mbaiwa and Mbaiwa 2006). This problem is likely to intensify as climate change increases the need for wildlife to travel further or find novel routes to obtain sufficient food or water (Shrader *et al.* 2010). By restricting wildlife mobility, fences also have the potential to increase and alter the distribution of grazing pressure within a PA (Chase & Griffin 2009; Loarie *et al.* 2009; Vanak *et al.* 2010) and impact predator-prey interactions by modifying predation patterns (van Dyk & Slotow 2003; Dupuis-Désormeaux *et al.* 2016b) and causing certain species of predators to exceed a PA's carrying capacity (Packer *et al.* 2013a). Further, by isolating populations, fences render wildlife vulnerable to inbreeding and increase the need to manage small populations for genetic diversity (Trinkel *et al.* 2008; Miller *et al.* 2013).

From a social perspective, fences can infringe on land rights, limit the ability of people to access resources, interfere with travel routes, and generate conflicts with nearby communities (Twyman *et al.* 2001; Spierenburg & Wels 2006; Hoole & Berkes 2010). Fences are also vulnerable to vandalism, including the theft of wire that can be used to make snares—thereby exacerbating bushmeat hunting and undermining the conservation benefits that fences are often intended to provide (Gadd 2012; Lindsey *et al.* 2012). Compounding these issues, fences can be expensive to construct and challenging to maintain, necessitating trade-offs between effectiveness, labour, and cost (Durant *et al.* 2015; Trinkel & Angelici 2016).

Fencing is a particularly relevant management tool in Africa, where PAs containing large populations of megafauna often exist near human communities, leading to intense human-wildlife conflicts and threatening species with habitat loss, poaching, retaliatory killings for crop damage or livestock losses, and bushmeat hunting (Lindsey *et al.* 2017a). To date, the majority of Africa's wildlife fences have been constructed in Southern Africa and in Kenya (Trinkel & Angelici 2016). However, support for fencing as a wildlife management tool continues to grow across the continent: in 2015 Malawi began fencing Liwonde National Park (African Parks 2015); in 2016 Uganda's president promised to erect a fence around Queen Elizabeth National Park (Kahungo 2016); and in 2017 Benin announced plans to fence 190 km of Pendjari National Park (Sasse 2017).

Despite the recent attention focused on fencing, much remains unknown about its economic, ecological, and social impacts (Durant *et al.* 2015). In this study, we sought to shed light on these issues by surveying experts on fenced and unfenced PAs across Africa to identify the circumstances under which fencing might be an effective and appropriate conservation tool.

METHODS

Expert surveys

We conducted two types of surveys regarding the use of fencing around African PAs (following the methods of Lindsey *et al.* 2017b). First, from 2015 to 2016, we conducted 'unfenced surveys,' whereby we surveyed experts familiar with unfenced PAs to assess whether and why they would support or oppose the use of fencing at their respective PAs. Second, from 2016 to 2017, we conducted 'fenced surveys,' whereby we surveyed experts at fenced PAs to assess the advantages, drawbacks, and management issues associated with the use of fencing. We conducted separate surveys because we sought to answer related but separate questions regarding fenced and unfenced PAs. Specifically, with respect to fenced PAs, we sought to assess various financial, social, and ecological issues related to the use of fencing where it currently exists; with respect to unfenced PAs, we sought to assess the circumstances under which fencing is desired or opposed, as well as the expected impacts of fencing at unfenced PAs and how they compare to the experienced impacts of fencing at fenced PAs. In addition, our survey of unfenced PAs was undertaken within a broader survey concerning lion conservation in general, and we built upon the availability of unfenced survey data to conduct a second survey for comparison against the characteristics of fenced PAs. Surveyed experts consisted of individuals with in-depth knowledge about the salient issues at a particular PA (Hagerman & Satterfield 2014), including PA officers, managers, and researchers, and state wildlife authority officials.

We identified PAs using snowball sampling (Knapp 2012) and assessed state-run PAs as well as privately and communally run wildlife areas and conservancies (Lindsey *et al.* 2017b).

For unfenced PAs, our survey covered five topics about the PA in question: (1) general characteristics; (2) professional background of the respondent; (3) whether the respondent supported or opposed the use of fencing; (4) whether various factors weighed in favour of or against the use of fencing; and (5) the intensity of various threats to the PA's wildlife. Estimates of PA budgets were based on Lindsey *et al.* (2017b) and converted to dollars per km of PA perimeter. For fenced PAs, survey questions covered 10 topics about the PA in question: (1) general characteristics; (2) professional background of the respondent; (3) reasons for the use of fencing; (4) pros and cons of fencing; (5) structure of fencing in place; (6) costs of fencing (converted to 2017 U.S. dollars); (7) inspection and maintenance of fencing; (8) effectiveness of fencing; (9) ecological impacts of fencing; and (10) vandalism and community issues.

Surveys included open-ended, closed-ended, and Likert-scale questions (Appendix S2). All surveys were conducted via phone and/or email. We surveyed one respondent for each PA except for a small number of unfenced PAs, where one respondent completed multiple surveys, and a small number of fenced PAs (6%; n=4), where surveys were completed by more than one respondent. For PAs where respondents could not provide areas (n=3) or perimeter lengths (n=9), we obtained this information from the World Database on Protected Areas (IUCN/UNEP WCMC 2007).

Statistical analysis

All statistical tests were performed using R (R version 3.4.4; R Development Core Team 2016). Not all respondents answered all survey questions; accordingly, descriptive statistics are reported based on the number of responses received. We used non-parametric Wilcoxon rank-sum tests to compare support for fencing at unfenced PAs according to PA threats; fencing budget according to PA type (state-run versus non-state-run); fence maintenance according to PA type and fencing budget; and the estimated frequencies of wildlife escapes at PAs with and without predator-proof structures. We used ANOVA to compare the effectiveness of fencing at containing various wildlife species. We used Chi-square tests to compare the sufficiency of funding based on PA type and the frequency of fence inspection based on fencing budgets.

We ran two statistical analyses to explore which factors best predicted support for fencing in unfenced PAs and how these factors varied regionally. In each, we examined how support for fencing (binary variable of 'support' or 'do not support') varied with 14 predictor variables: PA shape (calculated as the ratio of perimeter/area); mean human density within 5 km of the PA (calculated using LandScan 2014™ High Resolution Global Population Dataset; available at http://web.ornl.gov/sci/landscan); mean cattle density within 5 km of the PA (calculated using data from Robinson *et al.* 2014); and threat scores (reported by respondents on a scale of 0-5) for human encroachment, livestock encroachment, bushmeat harvesting, commercial poaching, human-wildlife conflict, mining, logging, charcoal harvesting, trophy hunting, excessive ration hunting, and disease. For the first analysis, we built three nested logistic regression models to explore region-specific predictors of support for fencing: (1) a model based on data from all PAs in all regions (n=111 PAs with complete predictor data); (2) a model containing data from PAs in East Africa (n=40) and; (3) a model containing data from PAs in Southern Africa (n=55). Following standard methods of multimodel inference, we ran univariate models of all covariates and retained models with some empirical support (ΔAIC_c of ≤ 7; Burnham and Anderson 2004). Models were discarded if the candidate variable was correlated at $|r| \geq 0.70$ with stronger predictors (as determined by AIC_c). We then built multivariate models with all possible combinations of this variable set and ranked models by AIC_c, where lower AIC_c indicated better fit. We considered models with ΔAIC of < 7 to be strong predictors of support for fencing. Because PAs in West Africa showed unanimous support for fencing (support in all 10 PAs) and PAs in Central Africa showed near-unanimous lack of support for fencing (no support in 6 out of 7 PAs), these regions were not suitable candidates for multimodel inference. Consequentially, we conducted a second analysis using one-way ANOVA tests with 'region' as a blocking factor, followed by Tukey post-hoc tests, to compare differences among regions for each variable.

RESULTS

We obtained data from experts regarding 121 unfenced PAs across 21 countries and 63 partially or fully fenced PAs across 10 countries, including state-run (n=115 unfenced, n=35 fenced), privately run (n=2 unfenced, n=27 fenced), and communally run (n=4 unfenced, n=1 fenced) PAs (Fig. 1; Appendix S1 in Supporting Information). Unfenced PAs ranged in size from 64 km^2 to 78,483 km^2 (median=3,046 km^2) and were significantly larger than partially or fully fenced PAs, which ranged from 37 km^2 to 52,800 km^2 (median=600 km^2; U=1,893, $p < 0.001$). (Hereafter we refer to partially and fully fenced PAs collectively as "fenced PAs" unless otherwise noted). The greatest number of fenced PAs surveyed (29%) were in South Africa, where fencing is required by law for PAs containing certain species (Lindsey *et al.* 2012).

At fenced PAs, the extent of fencing ranged from 9-100% of the PA perimeter, with 46% of PAs being partially fenced (< 90% enclosed by fencing) and 54% fully fenced (≥ 90% enclosed by fencing). Fences at 21% of PAs had no functional electrification, while 65% had functional electrification across at least 90% of the fence. Minimum voltage was maintained at a mean of 6.1 ± 1.7 SD kV (range=2.2-9.0 kV). The use of some form of predator-proofing to prevent lions

(*Panthera leo*) and other species from digging under the fence (e.g., buried fencing, a rock apron, or electrified tripwire) was reported at 43% of PAs.

Benefits and drawbacks

At fenced PAs, respondents reported that fencing had been installed primarily to mitigate human-wildlife conflicts (52% of PA, n=32). However, the most cited benefit of fencing at fenced PAs was the demarcation of the PA boundary and/or the prevention of unlawful encroachment onto the PA (cited by 61% of respondents, n=37), while the most cited drawback was cost (52%, n=30). At unfenced PAs, respondents similarly favoured fencing as a means of demarcating the PA boundary or preventing unlawful encroachment (35% of PAs, n=39), and considered the most significant drawback of fencing its potential to limit connectivity between wildlife populations (35%, n=39; Fig. 2).

Costs and maintenance

Surveyed PAs varied in terms of fence height and materials and the use of electrification and predator-proof structures. Considering this variation, the reported cost of fence construction ranged substantially, from $1,816 to $33,090 per km. However, because the fences in our study were constructed over several decades and we could not obtain data on the timing of expenditures, we were unable to determine actual costs of construction in 2017 U.S. dollars. Accordingly, we asked respondents to estimate how much the fence at their PA would cost if constructed ‘today’ (the year we administered our survey). The median estimated current cost of construction was $9,522 per km (interquartile range of $5,956 to $12,100 per km).

The median annual budget for fence inspection and maintenance was $174 per km (range of $0 to $1,642 per km). Of those respondents who provided budget data, only 46% (n=23) stated that the fencing budget at their PA was sufficient to adequately inspect and maintain the fence.

Sufficient funding was more likely among non-state-run (15 out of 24) than state-run PAs (8 out of 26; χ^2=3.861, df=1, p=0.049). The median stated annual budget required for adequate fence inspection and maintenance across all PAs was $487 per km (range of $80 to $4,241 per km). Of those PAs reporting both actual and necessary fencing budgets, the amount necessary for adequate fence inspection and maintenance was at least double the budgeted amount in 85% of cases (11 out of 13 PAs).

Fences were better maintained at PAs with sufficient fencing budgets (mean self-assessed maintenance score=4.6 ± 0.6 SD on a scale of 0-5) than at PAs without adequate budgets (mean=3.1 ± 1.6 SD; U=483, p < 0.001) and at non-state-run PAs (mean=4.4 ± 0.8 SD) than at state-run PAs (mean=3.1 ±1.8 SD; U=280, p=0.002; Table 1). At 59% of fenced PAs (n=32), fences were inspected at least daily, a frequency that was more likely at PAs with sufficient fencing budgets than at PAs without (χ^2=4.335, df=1, p=0.037; Table 1). Wildlife was reported as the greatest source of damage to fences on a scale of 0-5 in terms of severity (mean=3.0 ± 1.5 SD), followed by weather (mean=2.2 ± 1.6 SD) and people (mean=2.1 ± 1.6 SD). Thirty-three percent of respondents cited flooding and 11% cited vegetation short circuiting electrified wires as significant sources of fence damage.

Effectiveness

We assessed the effectiveness of fences erected primarily to mitigate human-wildlife conflict or contain a variety of wildlife species (n=48; we excluded from this analysis fences that were erected primarily for narrow purposes, such as limiting the spread of disease between wildlife and livestock or containing specific species). These fences were most effective at containing rhinos (*Ceratotherium simum* and *Diceros bicornis*; mean of 0.03 ± 0.05 SD estimated escapes per month) and least effective at containing leopards (*P. pardus*; mean=12.5 ± 14.6 SD estimated escapes per month) and digging species (e.g., warthogs [*Phacochoerus africanus*]; mean=11.3 ± 14.0 SD estimated escapes per month; $F[2, 101]=10.71$, $p < 0.001$; note that we did not survey respondents at unfenced PAs about wildlife movement).

Fencing materials and budgets strongly affected the ability of fences to contain wildlife. For example, PAs with predator-proof fences had fewer lion escapes than those without (mean=0.08 ± 0.11 SD versus 6.96 ± 12.54 SD estimated escapes per month, respectively; $U=72.5$, $p=0.006$). Escapes by lions, elephants (*Loxodonta africana*), and leaping species (e.g., kudu [*Tragelaphus* sp.], impala [*Aepyceros melampus*]) were substantially lower at PAs with sufficient fencing budgets (as assessed by respondents) than at PAs without, although the differences were less pronounced for rhinos, buffaloes (*Syncerus caffer*), hippos (*Hippopotamus amphibius*), leopards, and digging species (Fig. 3).

Ecological and social issues

Respondents from 60% of fenced PAs reported that fencing disrupted wildlife migrations and/or dispersals. Elephants were impacted at the most PAs (33%), followed by buffalo (13%), and wildebeest (*Connochaetes* sp.) (13%). Fences at 35% of PAs contained gaps intended to facilitate the passage of wildlife (primarily elephants) and/or people into and out of the PA, or to dissuade warthogs from digging under (and compromising) the fence. Several respondents commented that fencing had minimal impact on migration or dispersal because human use had already rendered the landscape surrounding the PA uninhabitable for wildlife.

Respondents from 64% of PAs (n=34) perceived that local communities strongly supported fencing and 15% perceived that local communities were at least somewhat supportive of fencing. Only 11% of respondents perceived that local communities were either somewhat or strongly opposed to fencing. However, respondents from 36% of PAs reported that the use of fencing caused some form of conflict with a local community. Conflicts resulted from claims that fencing improperly limited community access to water, grazing areas, and other resources within the PA; perceived encroachment of fencing onto community land; unrealised expectations about the ability of fencing to mitigate human-wildlife conflicts; dissatisfaction with fence maintenance; politicisation of fencing; and the interference of fencing with travel routes. Among respondents from fenced PAs with nearby communities, 53% (n=33) reported that portions of the fence at their PA had been vandalised for parts, including wire, solar panels, and offset brackets, and 37% (n=23) reported that there was evidence that fencing materials had been used to construct snares.

Expert support for fencing

At fenced PAs, 61% of respondents (n=38) strongly supported the use of fencing and another 16% at least somewhat supported the use of fencing at their PA. At unfenced PAs, 44% of respondents (n=53) supported the use of fencing at their PA; of those, 90% favoured the use of partial rather than complete perimeter fencing. At unfenced PAs where respondents supported the use of fencing, the median PA budget was $1,421 per km (interquartile range of $321-3,098 per km), median PA area was 3,365 km^2 (interquartile range of 1903–5,890 km^2), and median PA perimeter was 310 km (interquartile range of 206–431 km). Support for fencing was greatest in West Africa, where respondents from 100% of unfenced PAs (n=10) favoured the use of fencing, and lowest in Central Africa, where only 14% (n=1) did. In East and Southern Africa, support for fencing was comparable, with respondents from 36% (n=15) and 34% (n=27) of unfenced PAs favouring fencing, respectively.

The overall intensity of threats in a PA did not appear to affect support for fencing. At unfenced PAs, total threat score did not differ between PAs where respondents favoured the use of fencing (median [interquartile range] of 23.2 [17.5–27.5]) and those where respondents did not (median [interquartile range] of 18.4 [14.0–26.4]; $U=1828.5$, $p=0.144$). However, regression model and ANOVA results indicated that across unfenced PAs in all regions of Africa, support for fencing was associated with PAs with higher human and cattle density (within 5 km of PA boundary) and higher threats from bushmeat harvesting, livestock encroachment, and logging ($p<0.04$, see Appendix S3 for detailed ANOVA results; Fig. 4; Table 2). In East Africa, support was associated with higher human and cattle density and threats from livestock encroachment, logging, commercial poaching, and disease. In Southern Africa, support was associated only with bushmeat harvesting, livestock encroachment, and logging. PA shape and threats from human-wildlife conflict, mining, charcoal extraction, trophy hunting, and excessive ration hunting were not associated with support for fencing in any region. Tukey tests revealed that all PA characteristics and threat scores based on support for fencing in West Africa differed greatly from PAs in other regions, whereas Central, East, and Southern Africa did not differ significantly (Appendix S3).

DISCUSSION

The use of fencing is a divisive topic in the conservation community (Packer *et al.* 2013a; Creel *et al.* 2013; Packer *et al.* 2013b; Woodroffe *et al.* 2014). Our findings from 184 PAs across 23 countries inform the resolution of this controversy by identifying the circumstances under which fencing is likely to be an effective management tool and by clarifying the costs and benefits associated with its use. As explained below, we found that fences can play a key role in mitigating human-wildlife conflicts and preserving the boundaries of PAs in high human- and livestock-density areas. Yet fences can also burden human communities and disrupt ecological processes and, importantly, are often too expensive for wildlife authorities to effectively maintain.

To our knowledge, our study represents the first attempt to report the distribution of fencing across Africa and to assess attitudes towards fencing among conservation professionals. Currently, fencing is largely limited to Southern Africa and parts of East Africa; however, as Africa's human population continues to grow (United Nations 2017) and its landscapes become even more fragmented (Said *et al.* 2016), we expect the use of fencing to mitigate human-wildlife conflicts and protect isolated PAs in densely populated areas to become increasingly important and increasingly widespread.

As noted above, our results demonstrate that appropriately planned, designed, and maintained fences have the ability to mitigate human-wildlife conflicts, which can improve local livelihoods and limit the retaliatory killing of threatened species like elephants and lions (Lichtenfeld *et al.* 2015). This is evidenced by the strong community approval of fencing perceived by most respondents in our study, suggesting that fences can meaningfully limit the negative economic impacts of wildlife on people. By doing so, fencing can also generate other, less obvious benefits, such as improved relations between PAs and local communities, as communities may recognize and appreciate fencing as an effort by authorities to help protect people and their property (Fig. 2).

Fences are also an effective tool for limiting human and livestock encroachment onto a PA. Where a PA has no clearly demarcated boundary, encroachment is more likely and, in some cases, may even be unintentional (Lindsey *et al.* 2012). Fences can limit this problem by creating both a physical and a psychological boundary to deter people and livestock from entering a PA; in fact, this was the most cited benefit of fencing in our study. This may explain the broad support for fencing among PAs in West Africa, where population densities are generally highest on the continent (World Bank 2017) and where bushmeat hunting and livestock encroachment ranked as the leading PA threats. With Africa's population of 1.25 billion people projected to double by 2050 (United Nations 2017), pressure from people and livestock is likely to increase in at least some PAs. In those cases, the ability of fencing to preserve the integrity of a PA's boundaries will likely become more important with time.

In other situations, however, the use of fencing would be clearly inappropriate—particularly if it would threaten the welfare of local people. Where a river forms part of a PA's boundary, for example, fencing the river inside the PA may prevent people from accessing a vital source of water (while fencing the river out would prevent wildlife from accessing it). Interference with access to water was one of the primary sources of conflict caused by the fences in our study and, where that occurs, any benefits derived from fencing are likely to be outweighed by the undue burden imposed on the affected people. Moreover, fences are unlikely to be effective under such circumstances: notwithstanding the perceptions of strong community support for fencing shared by most respondents in our study, fences were still frequently vandalised. To many people, fences symbolise colonialism, appropriation, and exclusion (Spierenburg & Wels 2006), and erecting a fence without accounting for the interests of—and engaging with—local communities increases the likelihood that it will be undermined (Lindsey *et al.* 2012). Working with communities in the design, alignment, and maintenance of fences, on the other hand, is likely to improve support for fencing (particularly where employment is created), increase its effectiveness as a barrier to encroachment, and reduce instances of vandalism.

Further, where long-term funding is doubtful, fences are likely to be a waste of both time and money. While the initial investment required to erect a fence varied widely among the PAs in our study, such expenditures represent only a portion of the overall costs of fencing. Based on the median estimated current construction cost from our survey ($9,522 per km) and the median estimated budget required for adequate inspection and maintenance ($487 per km per year), the initial costs of construction will be equalled approximately every 20 years for a well-maintained fence. For the unfenced PAs in our study that supported fencing, the median PA budget was $1,421 per km of the PA's perimeter per year, meaning that adequate fence inspection and maintenance could require an annual budgetary increase of over 34% for a fully fenced PA (depending on the ability of fencing to offset other management costs; Packer *et al.* (2013a) note that fencing has the potential to significantly reduce the costs of successfully managing lion populations).

These costs represent a significant obstacle to adequate fence inspection and maintenance: respondents from less than half the fenced PAs we surveyed considered their PA's fencing budget to be sufficient—in most cases, less than half the amount required. Such budgetary shortfalls translate into infrequent fence inspections and poor fence maintenance. Among other things, underfunded PAs are ill-equipped to deal with issues like flooding, which was a problem at one-third of the PAs in our study and can damage or destroy fences, disrupt electrification, and make fences even more difficult to inspect and maintain (Garai and Carr 2001; Slotow 2012). As several respondents reported, without adequate maintenance, fences are largely ineffective at containing certain conflict-prone species like lions (Thouless & Sakwa 1995; Graham *et al.* 2009, Kesch *et al.* 2015). However, even with a well-maintained fence, containing lions can be challenging: maintenance efforts have minimal effect on the containment of digging species like warthogs (Fig. 3), and lions have been shown to readily use holes dug by other species (Kesch *et al.* 2014). In addition, because poorly maintained fences can introduce a vast supply of wire for making snares (Kesch *et al.* 2015; Kimanzi *et al.* 2015) and themselves become a source of conflict between communities and PA authorities (Anthony *et al.* 2010; Chaminuka 2010), erecting and then ignoring a fence is likely to make matters worse than erecting no fence at all. Given that wildlife authorities across Africa are already struggling with significant expenses and inadequate budgets (Lindsey *et al.* 2017a; Lindsey *et al.* 2017b), high costs make fencing an unrealistic option for many PAs.

Where fences are affordable, their ability to contain wildlife varies with species. Fences were best at containing rhinos and buffaloes and worst at containing leopards and digging species. Further, the impact of budgets on the ability of fences to contain wildlife is highly species-dependent. For example, estimates of fence transgressions were 19 times higher for elephants and over 120 times higher for lions at PAs with insufficient fencing budgets. These conflict-prone species are particularly costly to contain because expensive electrification and predator-proof structures are often necessary for fencing them in. While our study did not assess the costs of managing human-wildlife conflicts at unfenced PAs, our data on the costs of constructing and maintaining fences and their perceived effectiveness at mitigating human-wildlife conflicts may help PA managers at unfenced PAs assess whether fencing is likely to be an efficient conflict-mitigation tool at their PA.

The ability of fences to contain wildlife also entails their potential to interfere with migrations and dispersals (Cushman *et al.* 2016; Newmark 2008; Vanak *et al.* 2010), which was reported by respondents from 60% of the PAs in our study. Given the pernicious and ubiquitous effects of habitat fragmentation (Said *et al.* 2016), care should be taken to avoid further restricting landscape-level movements of wildlife where possible. In some cases, this may rule out the use of fencing altogether, as in Tanzania's Tarangire National Park, where wildlife rely heavily on seasonal dispersal areas outside the PA (Nelson *et al.* 2010). In other situations, maintaining wildlife movements may warrant the use of fence gaps, which can be placed to maximise opportunities for migration and dispersal and allow for the selective passage of species into and out of a PA, as in Kenya's Lewa Wildlife Conservancy (Dupuis-Désormeaux *et al.* 2016a).

However, in many places, large-scale movements of wildlife no longer exist due to human land conversion outside a PA. For these PAs, fences pose little risk of disturbing ecological processes, yet allow for the effective use of small "islands" of protected habitat by reducing edge effects in high-human-density areas. Examples of this can be seen in the successes of Rwanda's Akagera National Park and Malawi's Majete National Park, and in various South African reserves, where fencing has rendered small PAs remarkably effective at conserving lions (Lindsey *et al.* 2012; Packer *et al.* 2013a), cheetahs (*Acinonyx jubatus*; Buk *et al.* in press), and wild dogs (*Lycaon pictus*; Davies-Mostert *et al.* 2009). Even in these cases, however, fences can have negative ecological consequences, such as by altering predator-prey interactions (Dupuis-Désormeaux *et al.* 2016b), reducing gene flow (Miller *et al.* 2013), and leading wildlife populations to exceed a PA's carrying capacity (Packer *et al.* 2013a). One option for limiting these consequences is to create secure fenced corridors between isolated PAs to allow for the reestablishment of wildlife migrations and dispersals. Such corridors could decrease the costs of managing fenced populations and create an interconnected landscape of fenced PAs. Alternatively, the impacts of fragmentation could be reduced by facilitating the movement of individual animals between PAs to mimic natural dispersal patterns (Davies-Mostert *et al.* 2009; Miller *et al.* 2015; Buk *et al.* in press). Examples of such "managed metapopulations" include black rhinos (Brooks 1989; Foose *et al.* 1993) and white rhinos (Emslie *et al.* 2009) in Southern and East Africa and wild dogs in South Africa (Mills *et al.* 1998; Davies-Mostert 2010).

We acknowledge several limitations in our results. Because a number of our survey questions required estimates and opinions, there is necessarily a degree of imprecision, bias, and subjectivity in our data. In addition, although we surveyed 184 total PAs, we were unable to obtain data from a number of fenced and unfenced PAs in Africa. Finally, with respect to the effectiveness and costs of fencing, our results did not account for wildlife population densities, PA shape, costs of managing specific issues such as human-wildlife conflict, and other factors that might influence the frequency of fence transgressions. However, because the respondents to our surveys are experts on their respective PAs, our results are nonetheless valuable in assessing the major pros, cons, and management issues associated with the use of fencing. Future research should build on our study to investigate these additional issues and other PAs to more fully inform our understanding of the role of fencing in PA management and conservation.

Our study demonstrates that conservation professionals working in a substantial proportion of unfenced PAs in Africa believe that fencing is currently needed or will be needed in the future. In particular, support for fencing is associated with high human and cattle densities within 5 km of a PA's boundary, and high threats from bushmeat harvesting, livestock encroachment, and logging. Although fencing has become a controversial topic, our results show that assessing the expediency of fencing at any PA requires a nuanced and pragmatic approach. In some cases, fencing may be a sensible option, particularly where local human and livestock densities are high and adequate budgets for maintenance exist. However, where wildlife movements would be disrupted, long-term funding is lacking, or communities oppose the idea, fencing will likely be inappropriate (although, in some cases, the use of partial rather than complete perimeter fencing may alleviate these challenges). Decision-makers considering the use of fencing should weigh the costs, benefits, and management issues discussed above to determine if fencing is likely to be an efficient, effective, and ethical tool given the specific conditions at their PA.

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Table 1. Comparison of state-run and non-state-run protected areas (PAs) and PAs with and without sufficient fencing budgets. Average (mean ± SD) maintenance score was measured on a scale of 0 (extremely poor maintenance) to 5 (near-perfect maintenance). 'n' represents the number of PAs.

PA category	n_{PA}	Range of PA perimeter length (km)	Median fencing budget ($/km)	Percent of PA perimeter		Percent of PAs							
				> 90% fenced	> 90% fence electrified	Fence caused conflict with local communities	Fence vandalized for parts	Fencing used to construct snares	Fencing predator-proofed	Fence inspected daily	Fence inspected irregularly/ never	Fence disrupts wildlife migration/dispersal	Maintenance score
State-run	35	130 - 463	194	28	60	35	60	40	37	42	27	68	3.1 ± 1.8
Non-state	28	64 - 148	174	96	89	38	44	33	50	61	0	52	4.4 ± 0.8
Sufficient budget	23	78 - 201	349	73	87	33	48	30	65	74	0	45	4.6 ± 0.6
Insufficient budget	27	76 - 491	105	52	64	44	67	56	37	33	22	65	3.1 ± 1.6

Table 2. Results of logistic regression identifying the predictor variables associated with support for fencing in protected areas (PAs) in different regions of Africa, showing the five most top-ranked multivariate models for each region. NA indicates the variable was not included in the model.

Region*	Model rank	df	logLik	AICc	ΔAICc	Human density	Cattle density	Bushmeat	Livestock encroachment	Logging	Commercial Poaching	Disease	(Intercept)
All regions (n=111)	1	4	-68.28	144.94	0.00	NA	0.04	0.25	NA	0.21			-1.81
	2	4	-68.47	145.31	0.37	0.02	NA	0.23	NA	0.21			-1.82
	3	5	-67.49	145.55	0.61	0.01	0.02	0.26	NA	0.21			-1.98
	4	3	-69.69	145.60	0.66	NA	0.04	0.33	NA	NA			-1.75
	5	5	-67.53	145.64	0.70	NA	0.03	0.23	0.15	0.21			-2.10
East (n=40)	1	4	-14.17	37.49	0.00	NA	0.11		NA	NA	1.59	1.71	-9.63
	2	5	-13.91	39.59	2.10	0.01	0.11		NA	NA	1.70	1.89	-10.56
	3	5	-14.08	39.92	2.43	NA	0.11		NA	0.13	1.53	1.68	-9.64
	4	5	-14.13	40.02	2.53	NA	0.11		0.12	NA	1.57	1.70	-10.04
	5	6	-13.85	42.25	4.76	0.01	0.11		0.14	NA	1.68	1.89	-11.06
Southern (n=55)	1	2	-34.47	73.16	0.00			NA	NA	0.35			-1.03
	2	3	-33.40	73.27	0.11			NA	0.26	0.31			-1.43
	3	2	-35.22	74.67	1.51			NA	0.31	NA			-0.98
	4	3	-34.19	74.85	1.69			0.15	NA	0.29			-1.47
	5	3	-34.29	75.04	1.88			0.25	0.26	NA			-1.79

*n = sample size of PAs with complete response data for predictor variables

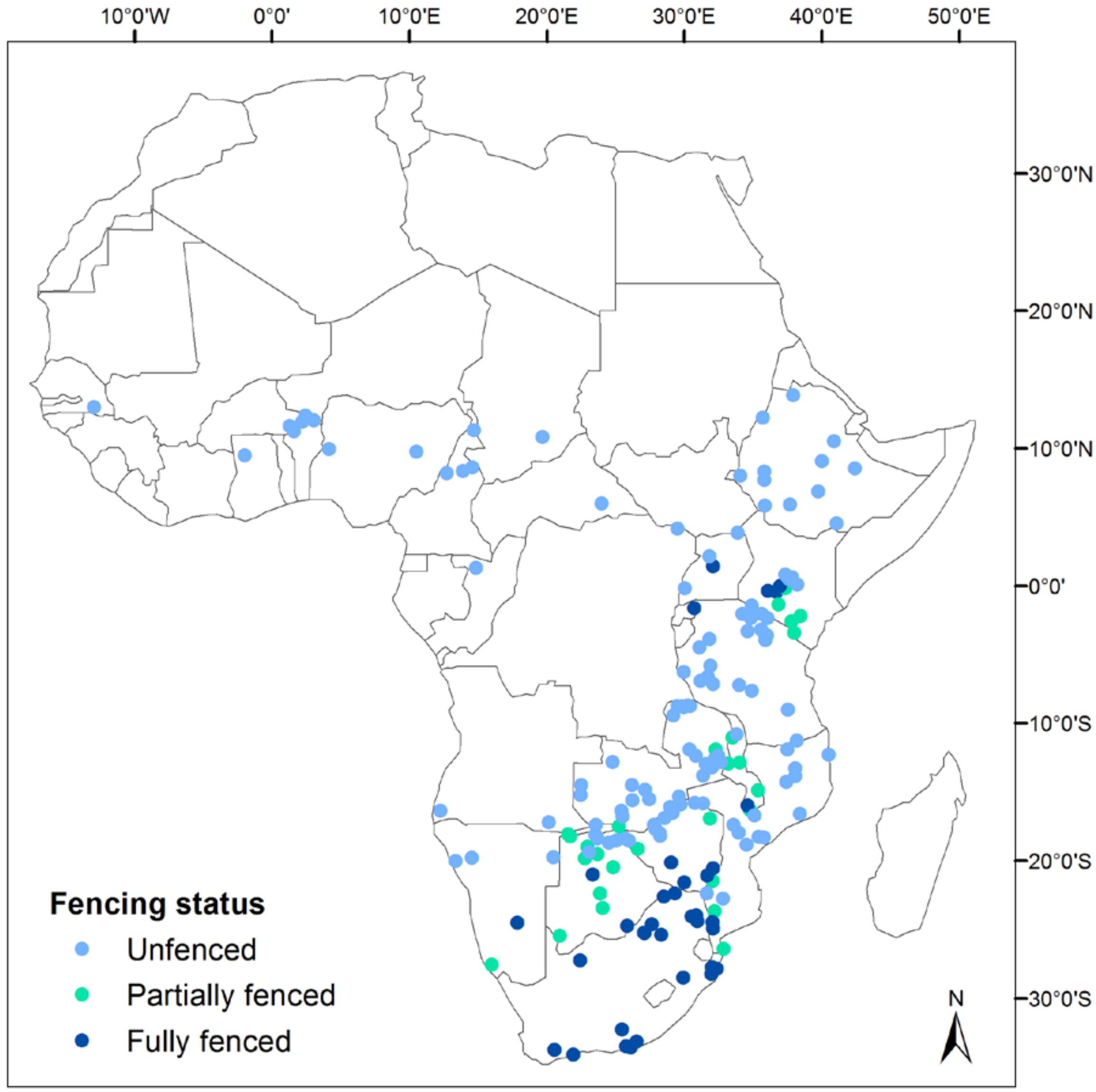

Fig. 1. Map of the 184 African protected areas (PAs) assessed, consisting of 121 unfenced (0% of perimeter fenced), 29 partially fenced (< 90% of perimeter fenced) and 34 fully fenced (≥ 90% of perimeter fenced) PAs.

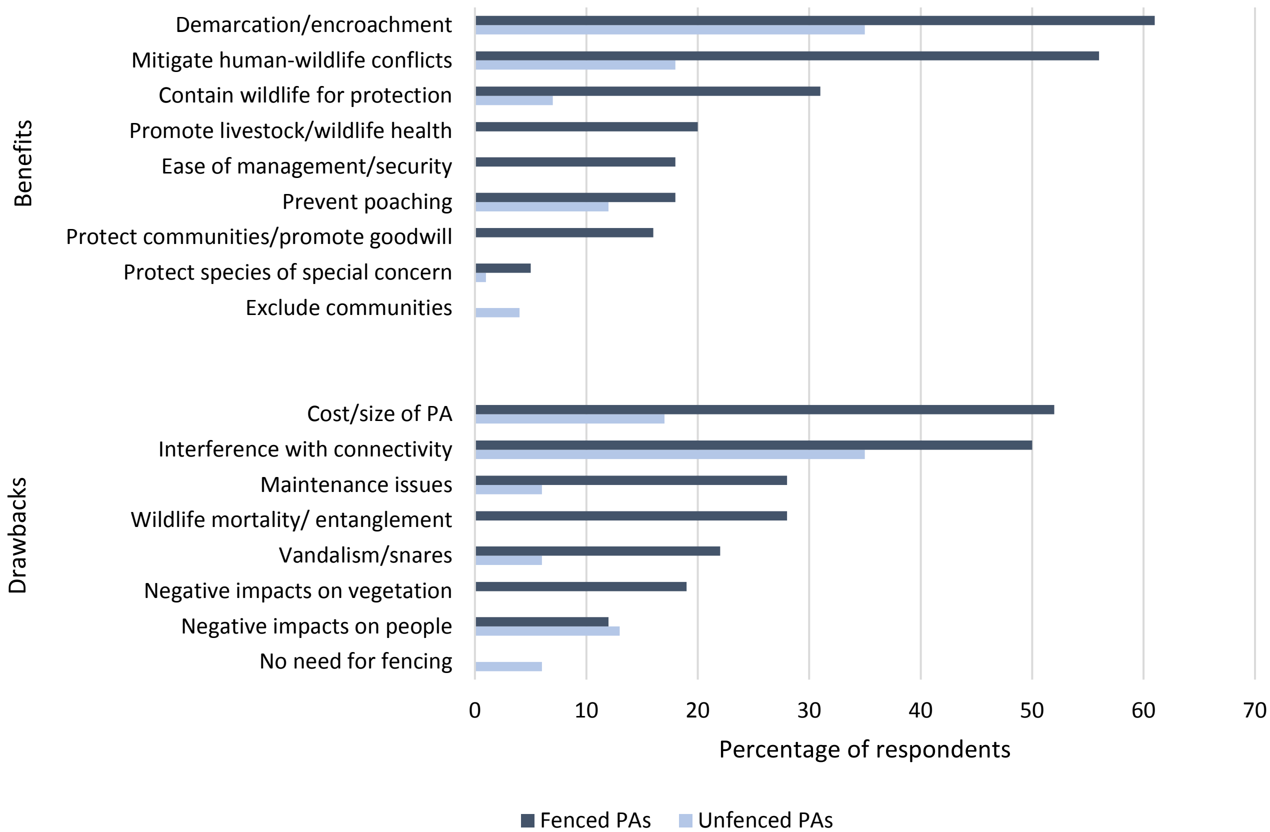

Fig. 2. Experienced and expected benefits and drawbacks of fencing cited by respondents from fenced and unfenced PAs, respectively.

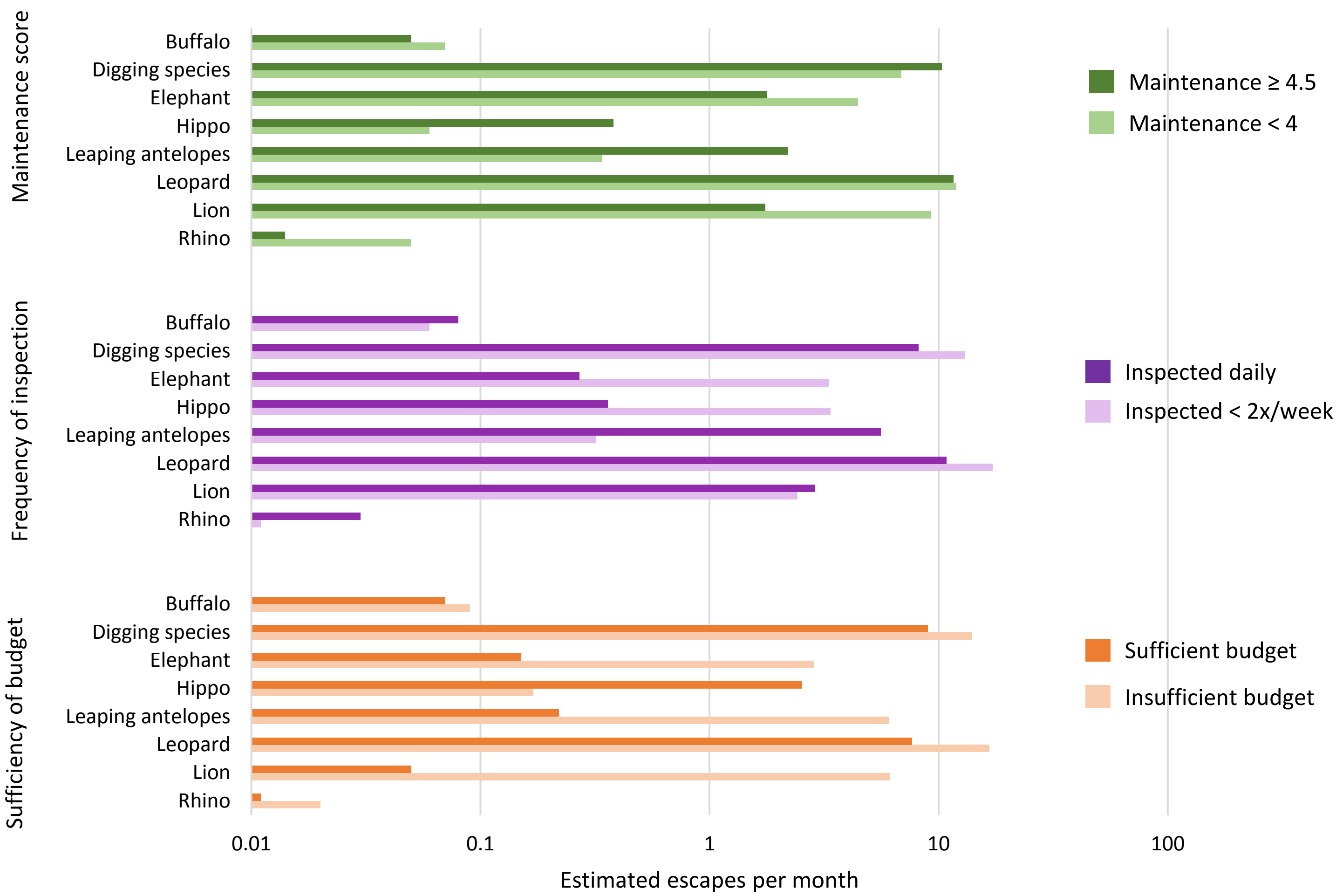

Fig. 3. Fences with poor care and investment, particularly infrequent inspections and insufficient budgets, lead to greater escapes by many wildlife species. Bars show the estimated escapes per month of various species or groups of species at fenced PAs based on (top) self-assessed maintenance score (≥4.5=dark green, <4=light green; maintenance assessed on a scale of 0 [extremely poor maintenance] to 5 [near-perfect maintenance]); (middle) frequency of inspection (inspected at least daily=dark purple, inspected twice per week or less=light purple); and (bottom) sufficiency of fencing budget (sufficient budget=dark orange, insufficient budget=light orange). Sample includes only PAs erected primarily to mitigate human-wildlife

conflict or contain a variety of wildlife species (i.e., not fences erected primarily for limited purposes such as preventing the spread of disease or containing specific species).

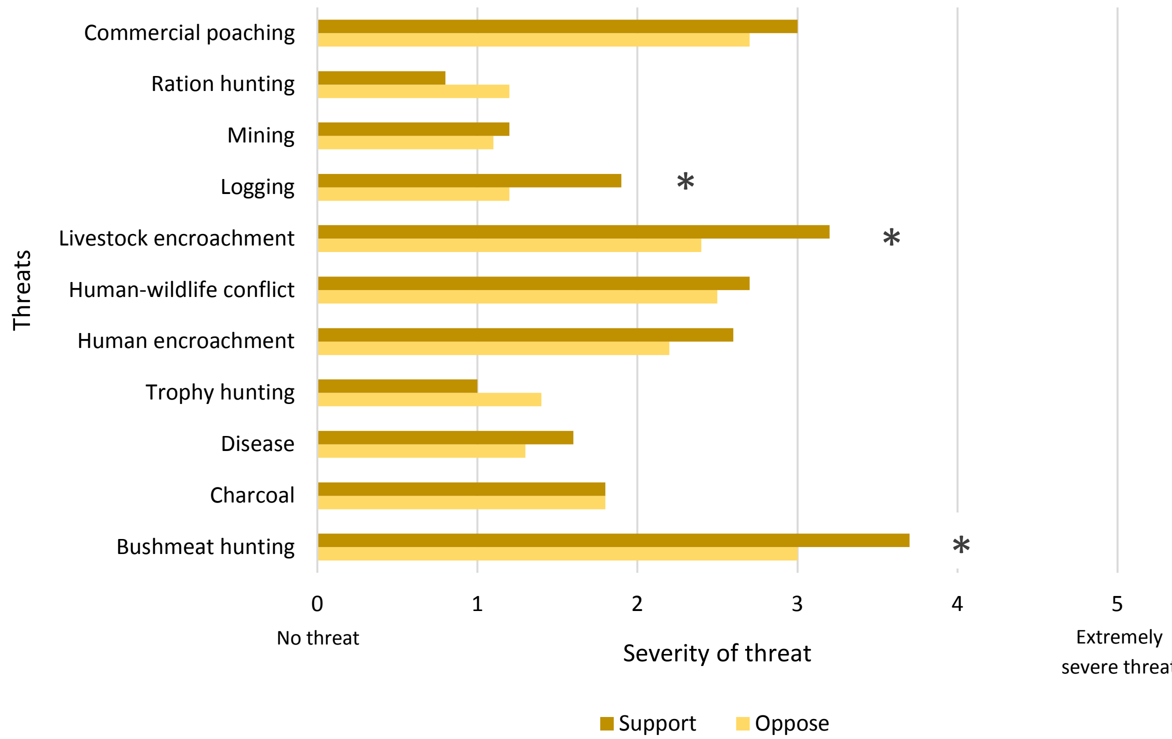

Fig. 4. Mean threat scores (on a scale of 0-5, with 0 indicating no threat and 5 indicating an extremely severe threat) to wildlife at unfenced PAs where respondents support (n=48) and oppose (n=63) the use of fencing. Asterisks indicate significant differences ($p<0.05$) between PA respondents who support versus oppose fencing.

Supporting Information

Fencing Africa's protected areas: Costs, benefits, and management issues

Appendix S1. Number of protected areas (PAs) surveyed by country, and percentage of PAs unfenced (0% of perimeter), partially fenced (1-90% of perimeter), and fully fenced (≥90% of perimeter). 'n' represents the number of PAs.

Country	n_{PA}	Unfenced (%)	Partially fenced (%)	Fully fenced (%)
Angola	2	100	0	0
Benin	2	100	0	0
Botswana	13	23	54	23
Burkina Faso	2	100	0	0
Cameroon	4	100	0	0
Central African Republic	1	100	0	0
Chad	1	100	0	0
Ethiopia	12	100	0	0
Ghana	1	100	0	0
Kenya	16	40	33	27
Malawi	8	25	62	13
Mozambique	19	83	11	6
Namibia	10	60	30	10
Niger	1	100	0	0
Nigeria	2	100	0	0

Republic of Congo	2	100	0	0
Rwanda	1	0	0	100
Senegal	1	100	0	0
South Africa	18	0	0	100
Tanzania	20	100	0	0
Uganda	4	75	25	0
Zambia	27	96	4	0
Zimbabwe	17	59	18	23

Appendix S2. Survey questions.

Survey type	Topic/question	Question type	Score rubric
Unfenced	Intensity of following threats to PA's wildlife: human encroachment; livestock encroachment; bushmeat harvesting; commercial poaching; human-wildlife conflict; disease; mining; logging; charcoal harvesting; trophy hunting; and excessive ration hunting.	Likert-scale	0 (no threat) to 5 (extremely severe threat)
	Annual PA management budget	Open-ended	n/a
	Role of fencing in PA management	Open-ended	n/a
	Extent of fencing supported	Open-ended	n/a
Fenced			
	Area and perimeter of the PA	Open-ended	n/a
	Whether any portion of the PA's perimeter is fenced	Yes/no	n/a
	Whether the PA's perimeter is entirely fenced	Yes/no	n/a
	The length of the fence	Open-ended	n/a
	The approximate dates of construction of the fence	Open-ended	n/a
	The most important reasons fencing was erected at the PA	Open-ended	n/a
	If the PA is not entirely fenced, the most important reasons certain sections of the PA were left unfenced	Open-ended	n/a

Structure of the fence (height, fence type (e.g., strand vs. mesh), single versus double fence, fence post materials)	Open-ended	n/a
Whether any portion of the fence is electrified	Yes/no	n/a
The percentage of the fence that is electrified	Open-ended	n/a
The source of electrification and the voltage at which the fence is maintained	Open-ended	n/a
Approximate cost of construction	Open-ended	n/a
Approximate cost if constructed today	Open-ended	n/a
Approximate annual budget for fence inspection and maintenance	Open-ended	n/a
Whether budget is sufficient for adequate fence inspection and maintenance	Yes/no	n/a
Amount necessary for adequate inspection and maintenance (while understanding the overall costs of managing wildlife is critical, our economic analysis focused specifically on the costs of constructing and maintaining fencing)	Open-ended	n/a
Whether the fence is regularly inspected	Yes-no	n/a
How often the fence is inspected	Open-ended	n/a
How well fence is maintained	Likert-scale	0 (extremely poor maintenance, whereby fallen and/or damaged sections of the fence regularly go unrepaired for extended periods of time) to 5 (near-perfect maintenance, whereby

		damage is almost always repaired within days).
How significant wildlife, weather, and people are as a source of fence damage	Likert-scale	0 (extremely insignificant) to 5 (extremely significant)
Pros and cons associated with the use of fencing	Open-ended	n/a
Effectiveness of fencing at excluding community members, poachers, and livestock	Likert-scale	0 (extremely ineffective) to 5 (extremely effective)
Frequency with which lions, leopards, elephants, rhinos, buffaloes, leaping species, and digging species are known, reported, or observed to escape from the PA	Likert-scale	0 (approximately daily), 1 (approximately weekly), 2 (approximately monthly), 3 (approximately every few months), 4 (approximately once per year), 5 (less than once per year or never)
Whether there are any gaps in the fence intended to facilitate the passage of wildlife into and out of the PA	Yes/no	n/a
Reasons for the use and placement of fence gaps	Open-ended	n/a
Whether fence gaps are used for large-scale migrations/dispersals	Yes/no	n/a
Negative consequences associated with use of fence gaps	Open-ended	n/a
Whether fencing has disrupted any large-scale migration/dispersals at PA and, if so, which species have been most effected	Open-ended	n/a

	Change in ecosystem health/functioning inside and outside PA since fence was erected	Likert-scale	Extremely negative, somewhat negative, no discernible change, somewhat positive, extremely positive
	Local community support for or opposition to the use of fencing	Likert-scale	Strongly oppose, somewhat oppose, neutral, somewhat support, strongly support, no local communities
	Whether fencing has caused any conflict with local communities and the nature of any such conflicts	Open-ended	n/a
	Whether fencing has been vandalized	Yes/no	n/a
	Whether there is evidence that fencing has been used to make snares and, if so, whether snares made from fencing have been found within the PA	Yes/no	n/a
	Change in number of snares found in PA since fencing installed	Likert-scale	Decrease, no discernible change, increase
	Respondent’s level of support for fencing at PA	Likert-scale	Strongly oppose, somewhat oppose, neutral, somewhat support, strongly support
	Reasons respondent supports or opposes use of fencing at PA	Open-ended	n/a
	Whether there are other important fencing-related issues to discuss	Open-ended	n/a

	Whether there are other fenced PAs in the region that we could contact for participation in the survey	Open-ended	n/a

Appendix S3. Regional variation in protected area (PA) characteristics and threats in PAs based on support for fencing. Bold numbers indicate significant differences between variables between PAs with and without support for fencing in one-way ANOVAs blocked by region ($p \leq 0.05$). Regions with common symbols were statistically different from one another in Tukey post-hoc tests ($p \leq 0.05$).

Variable	Mean value		ANOVA		Mean value by region and support for fencing (yes/no)											
	All regions		F[¶]	p-value	Central Africa			East Africa			Southern Africa			West Africa		
	Yes (n=48)	No (n=63)			Yes (n=1)	No (n=5)	Tukey	Yes (n=15)	No (n=25)	Tukey	Yes (n=22)	No (n=33)	Tukey	Yes (n=10)	No (n=0)	Tukey
PA shape (km^{-1})	0.12	0.16	1.84	0.178	0.12	0.13		0.17	0.20	*	0.10	0.13	†	0.09	NA	*†
Human density ($\#/km^2$)	**35**	**18**	**7.10**	**0.009**	77	8	*	67	31	†	13	9	‡	30	NA	*†‡
Cattle density ($\#/km^2$)	**19.3**	**7**	**4.58**	**0.035**	5	1	*	49	12	*	2	4	†	14	NA	*†
Human encroachment	2.6	2.2	1.28	0.261	5.0	2.6	*	2.5	2.1	†	3.0	2.2	‡	1.5	NA	*†‡
Livestock encroachment	**3.2**	**2.4**	**6.19**	**0.014**	5.0	4.2	*	4.0	3.4	†	2.8	1.4	‡	3.9	NA	*†‡
Bushmeat	**3.7**	**3**	**4.50**	**0.036**	5.0	4.8	*	2.9	2.5	†	4.0	3.2	‡	3.9	NA	*†‡
Commercial poaching	3	2.7	0.88	0.350	3.0	4.8	*	2.9	1.9	†	3.2	3.0	‡	2.8	NA	*†‡
Human-wildlife conflict	2.7	2.5	0.38	0.540	5.0	3.8	*	2.7	2.6	†	2.7	2.3	‡	2.3	NA	*†‡
Mining	1.2	1.1	0.04	0.851	5.0	3.0	*	1.4	1.0	†	1.4	1.0	‡	0.1	NA	*†‡
Logging	**1.9**	**1.2**	**7.02**	**0.009**	0.0	0.8	*	2.1	1.1	†	2.4	1.3	‡	0.9	NA	*†‡
Charcoal	1.8	1.8	0.02	0.893	0.0	2.0	*	2.7	2.6	†	1.8	1.2	‡	0.8	NA	*†‡
Trophy hunting	1	1.4	2.12	0.148	4.0	2.3	*	0.9	1.2	†	0.8	1.4	‡	1.0	NA	*†‡
Ration Hunting	0.8	1.2	1.41	0.238	0.0	0.5	*	0.8	0.5	†	1.2	1.8	‡	0.1	NA	*†‡
Disease	1.6	1.3	1.92	0.169	1.4	1.1	*	2.9	1.4	†	1.2	1.2	‡	1.4	NA	*†‡