frontiers | Frontiers in Conservation Science

TYPE Original Research
PUBLISHED 24 August 2023
DOI 10.3389/fcosc.2023.1237849

Check for updates

OPEN ACCESS

EDITED BY
Daniel Thornton,
Washington State University, United States

REVIEWED BY
Lyn Branch,
University of Florida, United States
Bin Wang,
China West Normal University, China

*CORRESPONDENCE
Vignesh Kamath
Vignesh.Kamath.Cannanure@unep-wcmc.org

†These authors share first authorship

‡These authors share senior authorship

RECEIVED 10 June 2023
ACCEPTED 26 July 2023
PUBLISHED 24 August 2023

CITATION
Kamath V, Brooks H, Naidoo R, Brennan A, Bertzky B, Burgess ND, McDermott Long O, Arnell A and Bhola N (2023) Identifying opportunities for transboundary conservation in Africa. *Front. Conserv. Sci.* 4:1237849. doi: 10.3389/fcosc.2023.1237849

Identifying opportunities for transboundary conservation in Africa

Vignesh Kamath[1*†], Holly Brooks[1†], Robin Naidoo[2,3], Angela Brennan[2], Bastian Bertzky[4], Neil D. Burgess[1,5], Osgur McDermott Long[1], Andy Arnell[1‡] and Nina Bhola[1‡]

[1]UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, United Kingdom, [2]WWF-US, Washington, DC, United States, [3]University of British Columbia, Vancouver, BC, Canada, [4]Woluwe-Saint-Pierre, Brussels-Capital Region, Belgium, [5]Center for Macroecology, Evolution and Climate, University of Copenhagen, Copenhagen, Denmark

The conservation of natural and cultural resources shared between countries is a significant challenge that can be addressed through the establishment of transboundary conservation areas (TBCAs). TBCAs enable countries to harmonize cross-border governance and management, increase protected area (PA) coverage, and strengthen relationships between neighbouring countries and communities. In Africa, many ecosystems and species ranges span multiple countries, making TBCAs a crucial tool for biodiversity conservation. However, there is a lack of research on where TBCAs can be established or need to be established. To address this gap, we conducted a study to identify opportunities for establishing TBCAs in Africa. We first compiled an up-to-date list of existing TBCAs on the continent. Then, we identified potential TBCAs by identifying protected areas next to country borders that are adjacent to other protected areas in a neighbouring country. We also evaluated the functional connectivity between these PA pairs and prioritized potential TBCAs based on size, connectivity, and ease of establishment. We identified 27 existing TBCAs and 8,481 potential TBCAs in Africa composed of various possible combinations of 2,326 individual PAs. Our results provide a baseline of existing TBCAs and offer a better understanding of where transboundary conservation might be established or strengthened. We also highlight areas where future transboundary conservation efforts could safeguard PA connectivity. This information can guide policy and decision-making processes towards promoting conservation and sustainable use of natural and cultural resources shared between countries in Africa.

KEYWORDS

transboundary conservation areas, functional connectivity, Kunming-Montreal Global Biodiversity Framework, protected areas, mammals

1 Introduction

Land- and seascapes are experiencing a loss of ecological connectivity (Bishop et al., 2017; Tucker et al., 2018). Ecological connectivity is defined as the "unimpeded movement of species and the flow of natural processes that sustain life on Earth" (CMS, 2020). Loss of ecological connectivity is caused by habitat loss, degradation and fragmentation (Haddad et al., 2015), which results from activities such as infrastructure development and land- or sea-use change (Bishop et al., 2017; Langlois et al., 2017; Tucker et al., 2018).

Loss of ecological connectivity can also result from the geopolitical boundaries that define countries (Liu et al., 2020). The demarcations made by nature and humans rarely align, and, as a result, country borders frequently intersect ecosystems and species ranges. Country borders can cause loss of ecological connectivity across land and seascapes because different parts of the same ecosystem can be managed separately by neighbouring countries and are often subjected to different governance, policy and legal frameworks (Vasilijević et al., 2015). Management and governance of shared transboundary ecosystems is often not holistic, but mismatched, and in some cases can be contradictory (Vasilijević et al., 2015; Thornton et al., 2018). Border infrastructure, such as fences, can also negatively impact biodiversity and connectivity (Trouwborst et al., 2016; Peters et al., 2018; Naidoo et al., 2022). As such, country borders can fragment species ranges, ecosystems and natural resources that span neighbouring countries and create barriers to ecological connectivity. It is important to note that these border barriers not only have environmental implications but can also have social and cultural consequences. For instance, they can divide indigenous peoples' and local communities' lands and territories, hindering their access to and use of cultural resources.

Many sites that are important to biodiversity are situated around country borders because borders are often placed in inaccessible or remote areas (Liu et al., 2020). One third of high-biodiversity sites straddle national land borders (Liu et al., 2020), and in the ocean, 90% of species have ranges that span international borders and/or international waters (Roberson et al., 2021). Given the high levels of biodiversity situated in the vicinity of country borders, there is an opportunity for significant biodiversity gains if the ecological connectivity and intactness of the ecosystems found there can be retained (Liu et al., 2020). Transboundary conservation is a tool that neighbouring countries can use to do this, by collectively protecting shared ecosystems, species, and natural and cultural resources, and preventing the loss of ecological connectivity.

Africa exemplifies the potential benefits of transboundary conservation, given that most country boundaries on the continent were demarcated without taking the flow of natural processes and the distribution of ecosystems and species into account (Englebert et al., 2002). The continent is home to the largest remaining assemblages of large mammals globally (Vynne et al., 2022), many of which have transboundary ranges (Davies-Mostert et al., 2012; Lindsey et al., 2017). As such, these species are dependent on well-connected networks of protected areas (PAs) that span multiple countries (Wegmann et al., 2014; Santini et al., 2016; Lindsey et al., 2017; Wall et al., 2021). However, these PAs can be exposed to many different policy, legal and governance regimes, highlighting the need for coordinated efforts between countries so that species are effectively conserved.

Areas cooperatively managed between neighbouring countries across country borders, consisting of PAs and/or multiple use areas, are known as transboundary conservation areas (TBCAs) (Vasilijević et al., 2015). TBCAs have a long history and were originally proposed as a means for peacekeeping (Quinn et al., 2012) to promote stability and strengthen relations between countries, and in doing so maintain ecological integrity across country borders for threatened species. These areas are recognized and supported and/or encouraged by several global and regional multilateral environmental agreements, such as the Convention on the Conservation of Migratory Species of Wild Animal (CMS), the Convention on Biological Diversity (CBD) and the World Heritage Convention, among others (Mason et al., 2020).

TBCAs can maintain ecological connectivity by supporting ecosystem functioning, nutrient cycling, species dispersal, migration and climate resilience across transboundary land- and seascapes (Hilty and Laur, 2021). They have also been shown to be more economically efficient in comparison to countries implementing conservation actions independently (Kark et al., 2009; Mazor et al., 2013; Mazor et al., 2014; Runting et al., 2015) and to provide a means of sharing knowledge and lessons learned between PA management authorities (Vasilijević et al., 2015).

To improve knowledge about future opportunities for creating TBCAs in Africa, we sought to identify areas for new or extended cooperation across national terrestrial borders. To do this, we firstly created a list of existing TBCAs, and then focused our analysis on other PAs not included in this list, but in close proximity to country borders (i.e., potential future TBCAs). We evaluated the degree of ecological connectivity between these PAs and others that are adjacent across the border to help prioritise those that could benefit from more harmonized/coordinated policies for transboundary conservation.

2 Materials and methods

2.1 Identifying existing TBCAs

To create a better understanding of where TBCAs are already established, we collated a list of existing TBCAs in Africa. To do this, we extracted available data on 'designated' TBCAs from the global TBCA list (Lysenko et al., 2007) and online websites and portals such as the Southern African Development Community (SADC), online TBCA portal (https://tfcaportal.org) and the Peace Parks Foundation website (www.peaceparks.org), and gathered information from protected area experts who work in the region. We also conducted a Google search whereby we searched for each country name in Africa followed by "transboundary protected area". The top 20 search results were checked for information on existing transboundary conservation areas. For each result, we recorded the details of the individual PAs each TBCA contains, including PA name and country. We cross-referenced the information with the World Database on Protected Areas

(WDPA) (UNEP-WCMC and IUCN, 2021) and recorded the WDPA ID and spatial data for each PA that is part of an existing TBCA. In addition, we enhanced this data by spatially identifying all PAs located within the boundaries of the SADC Transfrontier Conservation Areas. Only those PAs with signed treaties or memoranda of understanding (MoUs) were taken into account, while nested TBCAs were treated as singular entities.

2.2 Identifying potential TBCAs from PAs near borders

To identify future opportunities for TBCAs, we analysed existing terrestrial PAs that are within 100 km of a country border in Africa using data from the WDPA from November 2021 (UNEP-WCMC and IUCN, 2021). Of those PAs, we further identified those that are within 100 km of another PA that is situated across the border. We chose this large arbitrary threshold of 100 km to increase the number of possible combinations of PAs for transboundary conservation. We considered the dispersal and migratory distances of mammal species in Africa, many of which span hundreds of kilometres (Tshipa et al., 2017; van Hooft et al., 2018; Msoffe et al., 2019). For example, African wild dogs *Lycaon pictus* are known to disperse up to 360 km (Cozzi et al., 2020). Studies have found that large-scale transboundary initiatives contribute to the long-term viability of such wide-ranging species (Hofmann et al., 2021).

We used the IUCN's Type 1 and 2 definitions[1,2] of a TBCA for the purposes of this analysis. We refer to these pairs of PAs as 'potential TBCAs' and developed a working definition: *"A potential TBCA refers to a pair of PAs within 100 km of one another, situated in different countries and currently without some form of cooperation or coordinated management."* We considered both point and polygon data from the WDPA dataset. In the WDPA dataset, the 'status' of PAs provides information on whether the site is "designated", "established" or "proposed" (UNEP-WCMC and IUCN, 2021). We included PAs with status "proposed" in addition to "designated" and "established" since we are interested in future possibilities for TBCAs. We included those with status "not reported" and biosphere reserves (i.e., UNESCO MAB Biosphere Reserve) due to the preference of having commission errors rather than omission errors, to avoid excluding any important possible TBCAs. PAs under 0.5 km² were excluded from the analysis because they are unlikely to support populations of large and mobile mammals (Williams et al., 2022a). We carried out all the analyses in Azimuthal Equidistant projection centred on the centroid of mainland Africa (18.155074°, 6.989351°) to preserve the distance between PAs. We used RStudio 2021.09.0 + 351 "Ghost Orchid" Release (R Core Team, 2021) to conduct the analysis.

Of the potential TBCAs, we only excluded pairs of PAs found within the *same* existing TBCA. This allowed us to explore linking up different TBCAs, or for existing TBCAs to incorporate additional PAs.

2.3 Prioritising potential TBCAs

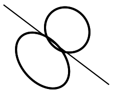
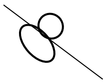
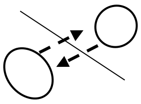
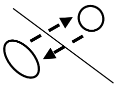
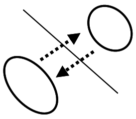
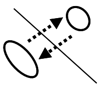
To support prioritisation of future TBCAs, we next grouped the potential TBCAs into six groups based on a combination of three ecological factors: (i) size, (ii) whether the PAs have boundaries that touch another PA, and (iii) their degree of connectivity for mammals between PAs. We chose these three factors as they influence a TBCA's ability to maintain or enhance connectivity (Beale et al., 2013; Dudley et al., 2014; Armsworth et al., 2018; Magris et al., 2018; Saura et al., 2018; Hilty and Laur, 2021). For each group, we stated an ecological objective to either maintain or enhance connectivity (Table 1).

For size, a PA size of >=1000 km² was chosen to indicate 'large' PAs. A large threshold was selected as larger PAs are more effective in conserving large-bodied mammals (Di Minin et al., 2013; Armsworth et al., 2018; Williams et al., 2022b). In the absence of specific guidance or rules regarding threshold of PA size, we opted for 1000 km² as a compromise to select a realistic number of 'large' PAs from the list of potential TBCAs. For whether the PAs had touching boundaries, the (Euclidean) distance between them had to be zero as this should ensure easy movement of species. To identify how ecologically connected the potential TBCAs are, we used a global resistance-to-movement surface layer created by Brennan et al. (2022) which maps landscape resistance to moving mammals. The 1-km² resistance surface that looked at the effects of human footprint on animal movement was developed based on Tucker et al. (2018) and used information on the movements of 624 GPS-tracked mammals of medium to large size from 48 species over 10 day periods (Brennan et al., 2022). For each PA pair, we calculated the Euclidean distance and the least-cost-distance (i.e., the cost weighted distance along the least cost path) between them, before calculating the ratio between the two (i.e., Euclidean distance/least cost-distance). A higher ratio denotes higher ecological connectivity indicating there are fewer barriers to movement through the landscape, such as human settlements or infrastructure. As such, the ratio can also be used as a proxy to indicate ecological condition for connectivity, with the assumption that fewer barriers to movement indicate more intact habitat. A connectivity rating in the top 10% of all TBCA ratings were considered 'well-connected', while the rest were categorized as 'less-connected'. We used the Makurhini (Godínez-Gómez and Correa Ayram, 2020) package in RStudio to run the connectivity analysis. We recognise the thresholds for size and degree of ecological connectivity are arbitrary and the analysis could be repeated using other thresholds.

1 **"Type 1: Transboundary protected area (TBPAs)**: A Transboundary Protected Area is a clearly defined geographical space that consists of protected areas that are ecologically connected across one or more international boundaries and involves some form of cooperation." (Vasilijević et al., 2015)

2 **"Type 2: Transboundary conservation landscape and/or seascape (TBCAs)**: A transboundary conservation landscape and/or seascape is an ecologically connected area that includes both protected areas and multiple resource use areas across one or more international boundaries and involves some form of cooperation." (Vasilijević et al., 2015)

TABLE 1 Six groups to help prioritise opportunities for new TBCAs from the potential TBCAs identified in the analysis, including the rationale for each group and high-level requirements for each group to become a TBCA.

Group	Objective	Rationale for prioritisation	Requirement/s to become a TBCA
1. Large – Touching 	Maintaining connectivity	• Both PAs over 1000 km² • Boundaries touch	Cooperative management
2. Small – Touching 		• One or both PAs are under 1000 km² • Boundaries touch	Cooperative management
3. Large – Well-connected 		• Both PAs over 1000 km² • Top 10% connectivity rating	Cooperative management Additional area-based management measures
4. Small – Well-connected 		• One or both PAs are under 1000 km² • Top 10% connectivity rating	Cooperative management Additional area-based management measures
5. Large – Less-connected 	Enhancing connectivity	• Both PAs are over 1000 km² • Connectivity rating below the top 10%	Cooperative management Additional area-based management measures Restoration
6. Small – Less-connected 		• One or both PAs are under 1000 km² • Connectivity rating below the top 10%	Cooperative management Additional area-based management measures Restoration

Three types of requirements are denoted: Cooperative management; Additional area-based management measures; Restoration.

Once the potential TBCAs were grouped, we also identified up to three high-level requirements that would be necessary for each group to become a TBCA, in order to provide a general idea of the level of steps required. The three requirements are: Cooperative management (by definition, all TBCAs require cooperative management); Additional area-based management measures (a new TBCA might require additional area-based management measures between its PAs e.g., an ecological corridor); and Restoration (degraded areas within a new TBCA may require restoration). The requirements denoted for each group are based on the combination of factors characterising each group (Table 1), i.e., assuming well-connected areas may require some level of protection/management and those that are less well-connected some level of restoration.

After grouping the potential TBCA into each group, we aggregated the results by country so that opportunities for new TBCAs with neighbouring countries can be identified at the country level.

3 Results

3.1 Identifying existing TBCAs

Through our review, we found that there are at least 27 existing TBCAs in Africa, covering an area of 847,158.60 km² (Figure 1). Most of these TBCAs are large complexes (median= 10,041 km²), comprised of numerous PAs (median=7 PAs) as well as other resource-use areas and have varied governance arrangements. We recognise that this list (Supplementary Table 1) may not be comprehensive and that it requires verification from national governments and PA management authorities.

3.2 Identifying potential TBCAs from PAs near borders

We found a total of 8,481 potential TBCAs, representing possible combinations of 2,326 individual PAs (3.3% of which have “proposed” status) and covering 1,970,228.16 km² (517, 587.89 km² i.e., 26.27% of which are already part of existing TBCAs). This areal extent overlaps with that of some existing TBCAs because some potential TBCAs contain a PA that is already part of an existing TBCA.

3.3 Prioritising potential TBCAs

We found the following number of potential TBCAs in each group: group 1 = 59; group 2 = 91; group 3 = 161; group 4 = 692; group 5 = 106; group 6 = 7,372. Potential TBCAs in different groups and existing TBCAs are displayed in Figure 1. Figures 1A, B show the range of examples of all categories of potential TBCAs. Some PAs can also be part of multiple groups of potential TBCAs. In situations where a PA belongs to more than one group, they are displayed on the map with

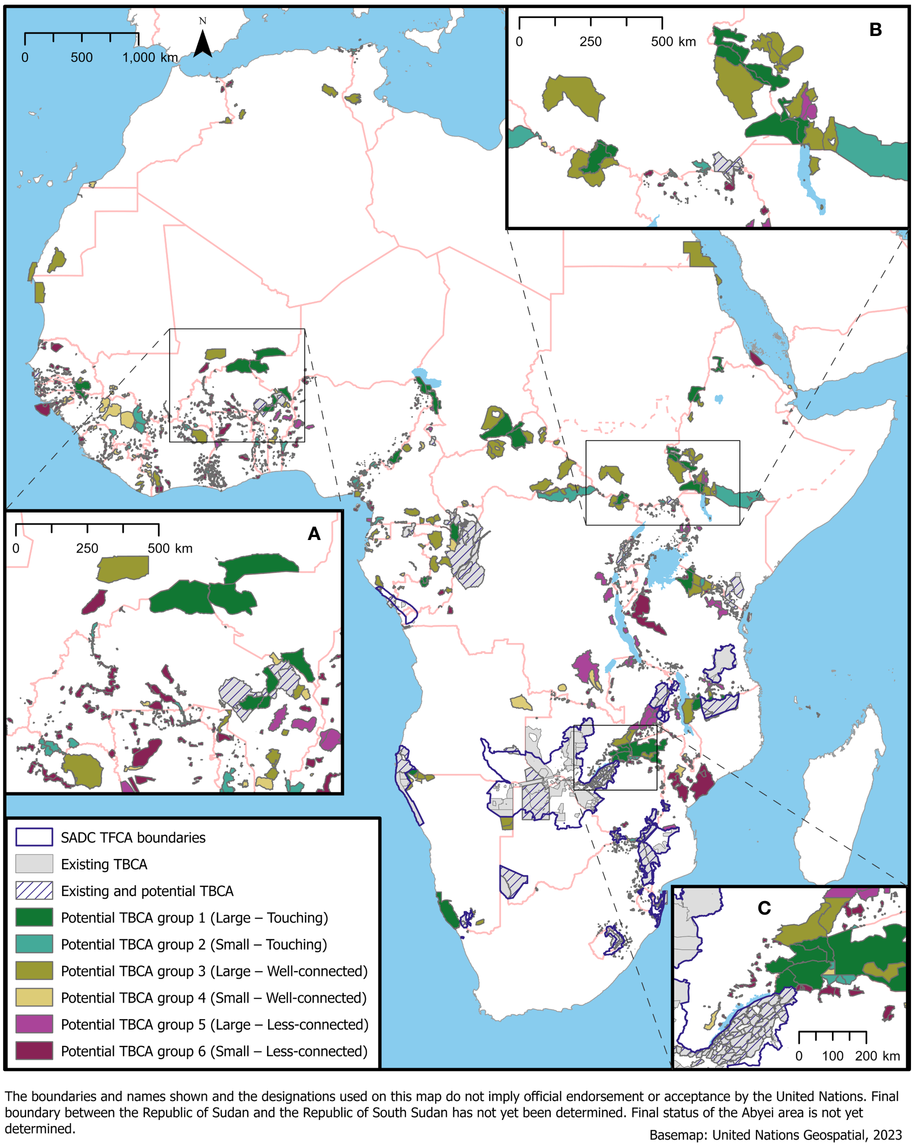


FIGURE 1
Potential and existing TBCAs in Africa. **(A)** and **(B)** show various examples of potential TBCAs across different categories. **(C)** shows an example of 'existing TBCAs' in grey and 'existing and potential TBCAs' indicated by hatched grey. The latter represents existing TBCAs that can also form potential TBCAs with other neighbouring PAs.

their highest priority group indicated (with group 1 representing the highest priority and group 6 representing the lowest). Additionally, some PAs that are part of existing TBCAs are displayed as 'existing and potential TBCAs' because they also form a new potential TBCA with a PA that is not yet part of the existing TBCA. Figure 1C shows an example of these two types of areas: existing TBCAs (shown in grey) and 'existing and potential TBCAs' (indicated by hatched grey). The latter represents existing TBCAs that also pair with neighbouring PAs across the border, thus forming potential TBCAs.

Figure 2 shows the number of potential TBCAs shared between different countries. Countries that share high numbers of potential TBCAs across all groups include Kenya and Tanzania, as well as Senegal and Gambia (Figure 2A). Countries that share the largest numbers in group 1 (large – touching) include Zimbabwe and Zambia (dark green PAs on the map in Figure 1C), Ethiopia and South Sudan (dark green PAs on the map in Figure 1B), Burkina Faso and Benin, and Burkina Faso and Niger (Figure 2B). Countries that share the largest numbers of potential TBCAs for maintaining connectivity (groups 1-4) include Zimbabwe and South Africa, and to a lesser extent Kenya and Tanzania, and Ethiopia and South Sudan (Supplementary Figure 1A). Countries that share the largest numbers for enhancing connectivity (groups 5-6) include Kenya and Tanzania, Senegal and Gambia, and Ghana and Côte d'Ivoire (Supplementary Figure 1B).

4 Discussion

Transboundary conservation areas (TBCAs) have the potential to protect ecosystems and species that straddle or move across country borders, thus maintaining and enhancing transboundary connectivity.

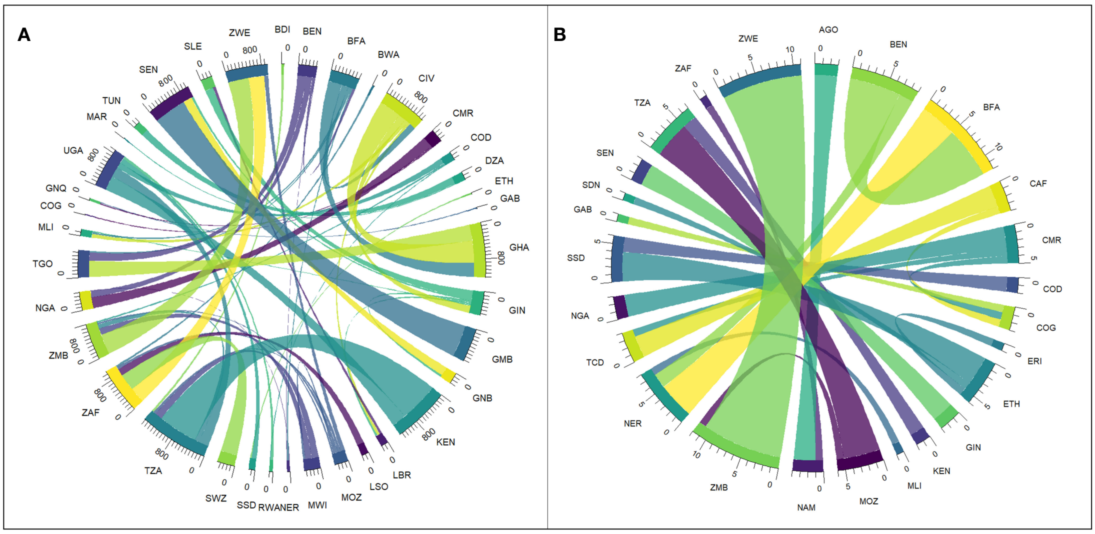


FIGURE 2
A depiction of the number of potential TBCAs between different countries (with ISO3 codes labelled). **(A)** groups 1-6, pairs of countries with <15 potential TBCAs between them were excluded from this figure. **(B)** group 1 (large – touching). Colours are only for clarity of visualisation.The list of country names with corresponding ISO3 codes can be found at https://www.iso.org/obp/ui/#search.

We set out to create a list of existing TBCAs and find opportunities for increasing TBCAs in Africa using a continental scale analysis.

4.1 Existing TBCAs

We found that there are at least 27 existing TBCAs in Africa. The majority are in southern Africa, although there are pockets in west and eastern Africa (Figure 1). Some of these TBCAs are well-established and highly successful. For example, the Greater Virunga Transboundary Protected Areas are situated between the Democratic Republic of Congo, Rwanda and Uganda, and has prevented some of the world's last remaining populations of endangered mountain gorillas *Gorilla beringei beringei* from becoming extinct (Robbins et al., 2011). In southern Africa, the SADC has a long history of establishing TBCAs and has an online portal where they are documented (https://tfcaportal.org), which is likely why more existing TBCAs (12 with a treaty/MoU signed) were found in this region. However, there is currently no centralised list of TBCAs across all of Africa. Although verification from national governments and PA management authorities is required, the list presented here can provide a starting point for compiling an updated list of TBCAs in Africa and a baseline against which progress to increase TBCAs in Africa can be tracked.

4.2 Maintaining connectivity

Potential TBCAs identified in the analysis with adjacent boundaries or with a connectivity rating in the top 10% (groups 1-4) are already well-connected. The establishment of a TBCA in these areas could provide protection against future threats, such as climate change in Africa and ensure transboundary connectivity is maintained to keep pace with range shifts. Requirements for these well-connected TBCA's range from 'cooperative management' only (groups 1-2, with touching PA boundaries) to both 'cooperative management' and 'additional area-based management measures' (groups 3-4, where PA boundaries do not touch but they are well-connected). For the latter, additional area-based management measures, such as ecological corridors, new PAs or other effective area-based conservation measures (such as community-based conservation efforts for enhancing landscape permeability), can be used to protect areas across the border in between the existing PAs and therefore help to maintain and enhance connectivity.

An example of a potential TBCA in group 1 (Large – Touching) is where the borders of Burkina Faso, Mali and Niger meet (Figure 1A). Here, there are three PAs that are all at least 1000 km^2, one in each country, with touching boundaries. Large PAs that form a TBCA can offer significant benefits to biodiversity because the expansive area that they collectively protect conserves large scale ecological processes (Armsworth et al., 2018). Expansive PAs also increase the amount of reachable PA for species, i.e. within their range of dispersal (Santini et al., 2016).

It is possible that potential TBCAs with touching boundaries (groups 1-2) already have some form of cooperative management, despite not being formally recognized as a TBCA (Zbicz, 2003). Establishing TBCAs from potential TBCAs that already have this type of informal cooperative management could be 'easy-wins' for increasing TBCA numbers, because many of the foundations for joint management are already in place. Formalising a TBCA can offer benefits such as attracting funding and harmonising national policies to facilitate further cooperative management (Schoon, 2013). Some existing TBCAs in Africa originated through informal management before progressing to formalisation, such as the Kgalagadi Transfrontier Park (Moswete et al., 2020). The Southern African Development Community TBCA online portal documents 'conceptual' TBCAs in addition to those that have a MoU or treaty signed (SADC, 2019). There is evidence that these bottom-up approaches to transboundary conservation tend to be more successful than top-down approaches (Schoon, 2013). However, formalising a TBCA requires financial resources, political will and legal instruments to enable the process (Lim, 2016). In some cases, formalising a TBCA where informal cooperative management is already taking place effectively might not offer any additional benefits to biodiversity, or could even be detrimental for conservation if undermining existing arrangements (e.g., with regard to community involvement). At the same time, informal management also carries inherent risks, such as the potential for lack of continuity when there is a change in local leadership. Therefore, potential TBCAs identified in this study should be considered on a case-by-case basis to establish whether there is already an informal system of cooperative management and, if so, whether this is sufficient to conserve biodiversity and transboundary connectivity.

Our calculation of connectivity rating is based on the assumption that there are no fences or border infrastructure between potential TBCAs that have touching boundaries (groups 1-2) and that species can move freely between them. Fences are sometimes used to manage wildlife within PAs in Africa, but predominantly as a means to prevent human-wildlife conflict (Cushman et al., 2016). It is unlikely that border infrastructure exists along portions of border where two PA boundaries touch; yet, if it does, the establishment of a TBCA would benefit from its removal due to the negative impacts fences and other border infrastructure are known to have on biodiversity and connectivity (Brennan et al., 2020; Naidoo et al., 2022).

Potential TBCAs that do not have touching boundaries but are highly connected (groups 3-4) can help ensure that mammals are able to move across borders and between the PAs. There are examples of several such potential TBCAs in this category on the borders of the Central African Republic, the Democratic Republic of Congo and South Sudan.

These potential TBCAs could be more at risk of connectivity loss compared to other potential TBCAs because the two, separately managed PAs are a distance apart and separated by a country border. There could be a risk of the intact habitat between these PAs becoming degraded due to threats such as land-use change (Aleman et al., 2016), caused by agriculture or infrastructure development, resource extraction and urban expansion (Simkin et al., 2022) and climate change (Senior et al., 2019), thereby reducing current transboundary connectivity. If this were to occur, there is a risk of the landscape becoming fragmented and these PAs becoming isolated. The establishment of a TBCA could mitigate and build resilience to threats, such as land-use change and climate change, thus proactively maintaining and enhancing current transboundary connectivity.

4.3 Enhancing connectivity

Of the potential TBCAs identified through the connectivity analysis, those that did *not* have a connectivity rating in the top 10% (groups 5-6) potentially stand to result in the largest biodiversity gains through the establishment of a TBCA. This is because a TBCA can provide the means for increasing connectivity between the two PAs through both cooperative management and, importantly, through additional measures such as ecological restoration, as identified in Table 1. Restoration of degraded habitats has a greater potential for increasing PA connectivity compared to only increasing the number of PAs, yet restoration and PA establishment together results in the largest benefits (Brennan et al., 2022). Restoration can also remove barriers and create ecological corridors (McRae et al., 2012) between PAs within TBCAs, thereby increasing transboundary connectivity. Smaller sized potential TBCAs (one or both <1000 km²) with a lower connectivity rating may have outsized ecological importance if they are situated within a heavily modified, fragmented landscape, where species have limited habitat and options for dispersal (Riva and Fahrig, 2022). These potential TBCAs may be a priority for transboundary conservation in order to prevent the negative impacts of PA isolation on biodiversity (Newmark, 2008; Prugh et al., 2008; Endo et al., 2019), and enhance transboundary connectivity.

4.4 Country results

The countries sharing higher numbers of group 1 (Large – Touching) potential TBCAs have a history of successful transboundary cooperation in the past. Notably, Zimbabwe and Zambia have collaborated through the Kavango Zambezi Transfrontier Park, while Burkina Faso and Benin, as well as Burkina Faso and Niger, have been jointly coordinating the W-Arly-Pendjari Complex. These country pairs have shared ecosystem/species and likely movement of animals. For example, one of the longest terrestrial mammal migration in Africa occurs between South Sudan and Ethiopia by the white-eared kob *Kobus kob leucotis* (Schapira et al., 2017). Similarly, Benin, Burkina Faso, and Niger share expansive savanna ecosystems and support substantial African elephant *Loxodonta africana* populations in the West African region (Lhoest et al., 2022). Given the presence of shared ecosystems and species movements across their borders, along with their history of successful cooperation, these countries are promising candidates for future transboundary initiatives. Such initiatives in these areas can build upon the existing successful partnerships further improving conservation efforts in these regions.

Additionally, certain neighbouring countries (like Kenya and Tanzania) have high numbers of shared potential TBCAs across multiple groups (Figure 2). Although not every potential TBCA in this analysis will benefit from becoming a TBCA and the effectiveness of a potential TBCA in achieving connectivity and biodiversity benefits is the priority, the numerous options identified for these pairs of countries warrants further investigation to see if any of their shared potential TBCAs are viable options.

4.5 Caveats

There are some caveats to our analysis. We looked at 'pairs' of PAs in order to explore the full possibilities of transboundary conservation, whereas in reality many TBCAs consist of more than two PAs. We did not attempt to group multiple PAs into possible TBCAs for simplicity. We also did not consider the feasibility of the potential TBCAs generated here. In reality, TBCAs have objectives beyond those related to biodiversity (e.g., generating socio-economic benefits, conserving cultural resources, or peacekeeping) and as such, the TBCAs presented here require further research before they can truly be considered as viable options for future TBCAs (Mason et al., 2020).

Our least-cost-distance analysis used the resistance surface developed by Brennan et al. (2022) which is based on medium to large-sized mammal movements data. Similar analyses on different taxa may yield different results. However, we anticipate that species from other taxa with similar dispersal abilities and ecological processes that depend on mammal movements (e.g., seed dispersal) should benefit.

The analysis used data from the WDPA. PAs that are not in this database will not have been included in this analysis. Additionally, our methodology was developed for use at the continental scale. It is not designed for use at finer scales at this time.

4.6 Further analyses

Our analysis was based on transboundary conservation and therefore focused on PAs adjacent to one another across country borders and how connected they are. This provides a snapshot of connectivity. Localised studies analysing connectivity between protected and unprotected areas can further inform how best to maintain and enhance connectivity across landscapes (Brennan et al., 2022). PAs adjacent to country borders but not within 100 km of a PA on the other side were excluded from our analysis. These PAs warrant further investigation to identify whether they are connected to an unprotected area across the border that may have conservation value, e.g., key biodiversity areas, and therefore whether that land is worth protecting and cooperatively managing as a TBCA with the existing PA. There are potentially many TBCAs of this type that would be beneficial to explore through further analyses of PAs near country borders adjacent to areas of importance for biodiversity across the border. Follow up studies to identify important potential TBCAs could also incorporate wider biodiversity considerations within the PAs, such as degree of endemism or inclusion of focal species.

Our analysis focused on PAs adjacent to country borders, but in reality, they are part of a national network of PAs. Those that were found not to be well-connected with equivalents across the border may in fact be well-connected to PAs within the same country but further from the border. Our analysis does not consider this wider ecological connectivity and further supports the need for additional connectivity analyses at the local, national and regional levels.

The methodology used in our analysis can be adapted to support different prioritisation needs. We grouped potential TBCAs into six groups based on PA size, whether the PA boundaries are touching and degree of connectivity. Different approaches to grouping TBCAs could be used based on the user's priorities, such as the type of governance of the PAs (e.g., government-run versus community-conserved) in potential TBCAs, conservation objectives (e.g., for various flagship species or ecosystems), or creating several groups based on different degrees of connectivity. In addition, different distance thresholds could be used in the analysis.

Our methodology also holds the potential for application in other continents to identify potential TBCAs. Notably, studies have indicated that the Americas (Thornton et al., 2020) and Asia (Kamath et al., unpublished) have a significant number of large-sized PAs situated closer to borders than away from them, making these regions particularly well-suited for investigating the potential for transboundary conservation.

4.7 Policy

Transboundary conservation is gaining political momentum. In 2021, the United Nations General Assembly adopted Resolution 75/271 "Nature knows no borders" on transboundary conservation, highlighting the importance of transboundary cooperation for biodiversity conservation, restoration and sustainable use (United Nations, General Assembly [UNGA], 2021). In December 2022, Parties to the Convention on Biological Diversity (CBD) adopted the Kunming-Montreal Global Biodiversity Framework (CBD, 2022). Under Target 3 of the Framework, Parties will establish a network of protected and conserved areas covering 30% of the world's land and oceans by 2030. In addition, Parties to the Convention on the Conservation of Migratory Species of Wild Animals (CMS) have recognized the importance of TBCAs to improve the quality of protected and conserved area networks. As countries in Africa look to increase their TBCAs, the results presented here provide a useful preliminary assessment of various priorities aligned with objectives such as maintaining or enhancing connectivity.

5 Conclusion

Transboundary conservation is essential for conserving ecological connectivity and biodiversity that spans country borders in Africa. Particularly in the face of climate change, PA networks need to be designed and developed to secure and maintain ecological connectivity and enable the movement of species and continued function of ecological processes. The continental scale analysis presented here highlights potential opportunities for new TBCAs and can be used as a starting point for countries to explore their options with their neighbours to help ensure positive outcomes for nature and for people across Africa.

Data availability statement

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

Author contributions

VK: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Review & Editing, Visualization. HB: Writing - Original Draft, Conceptualization, Methodology, Validation, Writing - Review & Editing, Data Curation, Project administration, Funding acquisition; RN: Methodology, Resources, Writing - Review & Editing. AB: Resources, Writing - Review & Editing. BB: Methodology, Writing - Review & Editing. NDB: Writing - Review & Editing. OM: Methodology, Software, Writing - Review & Editing. AA: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - Review & Editing, Supervision. NB: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Funding

The European Union (EU) provided funding through The Secretariat for the Convention on the Conservation of Migratory Species of Wild Animals (CMS) project, as part of the ongoing 'Cross-Regional Wildlife Conservation in Eastern and Southern Africa and the Indian Ocean' Programme and the Arcadia Fund in support of Protected Planet. The Open access was paid by UK Research and Innovation's Global Challenges Research Fund under the Trade, Development and the Environment Hub project (project number ES/S008160/1).

Acknowledgments

The authors would like to express their gratitude to the reviewers for key insights and comments, and we thank Andrea S. Dekrout, Brian MacSharry, Cleo Cunningham, Javier Fajardo, Jackson McQueeny, Joe Gosling, Kelly Malsch and Matt Kaplan for technical assistance.

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

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2023.1237849/full#supplementary-material

References

Aleman, J. C., Blarquez, O., and Staver, C. A. (2016). Land-use change outweighs projected effects of changing rainfall on tree cover in sub-Saharan Africa. *Glob. Change Biol* 22, 3013–3025. doi: 10.1111/gcb.13299

Armsworth, P. R., Jackson, H. B., Cho, S.-H., Clark, M., Fargione, J. E., Iacona, G. D., et al. (2018). Is conservation right to go big? Protected area size and conservation return-on-investment. *Biol. Conserv.* 225, 229–236. doi: 10.1016/j.biocon.2018.07.005

Beale, C. M., Baker, N. E., Brewer, M. J., and Lennon, J. J. (2013). Protected area networks and savannah bird biodiversity in the face of climate change and land degradation. *Ecol. Lett.* 16, 1061–1068. doi: 10.1111/ELE.12139

Bishop, M. J., Mayer-Pinto, M., Airoldi, L., Firth, L. B., Morris, R. L., Loke, L. H. L., et al. (2017). Effects of ocean sprawl on ecological connectivity: impacts and solutions. *J. Exp. Mar. Bio. Ecol.* 492, 7–30. doi: 10.1016/J.JEMBE.2017.01.021

Brennan, A., Beytell, P., Aschenborn, O., Du Preez, P., Funston, P. J., Hanssen, L., et al. (2020). Characterizing multispecies connectivity across a transfrontier conservation landscape. *J. Appl. Ecol.* 57, 1700–1710. doi: 10.1111/1365-2664.13716

Brennan, A., Naidoo, R., Greenstreet, L., Mehrabi, Z., Ramankutty, N., and Kremen, C. (2022). Functional connectivity of the world's protected areas. *Science* 376, 1101–1104. doi: 10.1126/science.abl8974

CBD (2022) *Kunming-Montreal Global Biodiversity Framework. Decision adopted by the Conference of the Parties to the Convention on Biological Diversity*. Available at: https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

CMS (2020). *Improving Ways of Addressing Connectivity in the Conservation of Migratory Species, Resolution 12.26 (REV. COP-13)* (Gandhinagar, India: UNEP/CMS/COP-13/CRP). Available at: https://www.cms.int/sites/default/files/document/cms_cop13_res.12.26_rev.cop13_e.pdf.

Cozzi, G., Behr, D. M., Webster, H. S., Claase, M., Bryce, C. M., Modise, B., et al. (2020). African wild dog dispersal and implications for management. *J. Wildl. Manage.* 84, 614–621. doi: 10.1002/jwmg.21841

Cushman, S. A., Elliot, N. B., Macdonald, D. W., and Loveridge, A. J. (2016). A multi-scale assessment of population connectivity in African lions (Panthera leo) in response to landscape change. *Landsc. Ecol.* 31, 1337–1353. doi: 10.1007/s10980-015-0292-3

Davies-Mostert, H. T., Kamler, J. F., Mills, M. G. L., Jackson, C. R., Rasmussen, G. S. A., Groom, R. J., et al. (2012). Long-distance transboundary dispersal of African wild dogs among protected areas in southern Africa. *Afr. J. Ecol* 50, 500–506. doi: 10.1111/j.1365-2028.2012.01335.x

Di Minin, E., Hunter, L. T. B., Balme, G. A., Smith, R. J., Goodman, P. S., and Slotow, R. (2013). Creating larger and better connected protected areas enhances the persistence of big game species in the Maputaland-Pondoland-Albany biodiversity hotspot. *PloS One* 8, e71788. doi: 10.1371/journal.pone.0071788

Dudley, N., Groves, C., Redford, K. H., and Stolton, S. (2014). Where now for protected areas? Setting the stage for the 2014 World Parks Congress. *Oryx* 48, 496–503. doi: 10.1017/S0030605314000519

Endo, C. A. K., Douglas, F. M. G., Ponzi Pezzi, L., and Lima, L. N. (2019). Low connectivity compromises the conservation of reef fishes by marine protected areas in the tropical south Atlantic. *Sci. Rep* 9 (1), 8634. doi: 10.1038/s41598-019-45042-0

Englebert, P., Tarango, S., and Carter, M. (2002). Dismemberment and suffocation: A contribution to the debate on african boundaries. *Comp. Polit. Stud.* 35, 1093–1118. doi: 10.1177/001041402237944

Godínez-Gómez, O., and Correa Ayram, C. A. (2020). *connectscape/Makurhini: Analyzing landscape connectivity (v1.0.0) Zenodo*. doi: 10.5281/zenodo.3771605

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., et al. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci. Adv.* 1, e1500052. doi: 10.1126/sciadv.1500052

Hilty, J. A., and Laur, A. T. (2021). Ecological networks and corridors in the context of global initiatives. *Park. Steward. Forum* 37 (3). doi: 10.5070/P537354730

Hofmann, D. D., Behr, D. M., McNutt, J. W., Ozgul, A., and Cozzi, G. (2021). Bound within boundaries: Do protected areas cover movement corridors of their most mobile, protected species? *J. Appl. Ecol.* 58, 1133–1144. doi: 10.1111/1365-2664.13868

Kark, S., Levin, N., Grantham, H. S., and Possingham, H. P. (2009). Between-country collaboration and consideration of costs increase conservation planning efficiency in the Mediterranean Basin. *Proc. Natl. Acad. Sci.* 106, 15368–15373. doi: 10.1073/pnas.0901001106

Langlois, L. A., Drohan, P. J., and Brittingham, M. C. (2017). Linear infrastructure drives habitat conversion and forest fragmentation associated with Marcellus shale gas development in a forested landscape. *J. Environ. Manage.* 197, 167–176. doi: 10.1016/j.jenvman.2017.03.045

Lhoest, S., Linchant, J., Gore, M. L., and Vermeulen, C. (2022). Conservation science and policy should care about violent extremism. *Glob. Environ. Change* 76, 102590. doi: 10.1016/j.gloenvcha.2022.102590

Lim, M. (2016). Governance criteria for effective transboundary biodiversity conservation. *Int. Environ. Agreements Polit. Law Econ.* 16, 797–813. doi: 10.1007/s10784-015-9296-3

Lindsey, P. A., Petracca, L. S., Funston, P. J., Bauer, H., Dickman, A., Everatt, K., et al. (2017). The performance of African protected areas for lions and their prey. *Biol. Conserv.* 209, 137–149. doi: 10.1016/J.BIOCON.2017.01.011

Liu, J., Yong, D. L., Choi, C.-Y., and Gibson, L. (2020). Transboundary frontiers: an emerging priority for biodiversity conservation. *Trends Ecol. Evol.* 35, 679–690. doi: 10.1016/j.tree.2020.03.004

Lysenko, I., Besançon, C., and Savy, C. (2007). *UNEP-WCMC Global List of Transboundary Protected Areas.* (Cambridge, UK: UNEP-WCMC).

Magris, R. A., Andrello, M., Pressey, R. L., Mouillot, D., Dalongeville, A., Jacobi, M. N., et al. (2018). Biologically representative and well-connected marine reserves enhance biodiversity persistence in conservation planning. *Conserv. Lett.* 11, e12439. doi: 10.1111/CONL.12439

Mason, N., Ward, M., Watson, J. E. M., Venter, O., and Runting, R. K. (2020). Global opportunities and challenges for transboundary conservation. *Nat. Ecol. Evol.* 4, 694–701. doi: 10.1038/s41559-020-1160-3

Mazor, T., Giakoumi, S., Kark, S., and Possingham, H. P. (2014). Large-scale conservation planning in a multinational marine environment: cost matters. *Source Ecol. Appl.* 24, 1115–1130. doi: 10.1890/13-1249.1

Mazor, T., Possingham, H. P., and Kark, S. (2013). Collaboration among countries in marine conservation can achieve substantial efficiencies. *Divers. Distrib.* 19, 1380–1393. doi: 10.1111/ddi.12095

McRae, B. H., Hall, S. A., Beier, P., and Theobald, D. M. (2012). Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. *PloS One* 7, e52604. doi: 10.1371/journal.pone.0052604

Moswete, N., Thapa, B., and Darley, W. K. (2020). Local communities' Attitudes and support towards the kgalagadi transfrontier park in southwest Botswana. *Sustainability* 12, 1524. doi: 10.3390/su12041524

Msoffe, F. U., Ogutu, J. O., Said, M. Y., Kifugo, S. C., de Leeuw, J., Van Gardingen, P., et al. (2019). Wildebeest migration in East Africa: Status, threats and conservation measures. *bioRxiv*, 546747. doi: 10.1101/546747

Naidoo, R., Beytell, P., Brennan, A., Kilian, W., McCulloch, G., Stronza, A., et al. (2022). Challenges to elephant connectivity from border fences in the world's largest transfrontier conservation area. *Front. Conserv. Sci.* 3. doi: 10.3389/fcosc.2022.788133

Newmark, W. D. (2008). Isolation of African protected areas. *Front. Ecol. Environ.* 6, 321–328. doi: 10.1890/070003

Peters, R., Ripple, W. J., Wolf, C., Moskwik, M., Carreón-Arroyo, G., Ceballos, G., et al. (2018). Nature divided, scientists United: US–Mexico border wall threatens biodiversity and binational conservation. *Bioscience* 68, 740–743. doi: 10.1093/biosci/biy063

Prugh, L. R., Hodges, K. E., Sinclair, A. R. E., and Brashares, J. S. (2008). Effect of habitat area and isolation on fragmented animal populations. *Proc. Natl. Acad. Sci. U. S. A.* 105, 20770–20775. doi: 10.1073/pnas.0806080105

Quinn, M. S., Broberg, L., and Freimund, W. (2012). *Parks, peace, and partnership: global initiatives in transboundary conservation.* (Calgary: University of Calgary Press). doi: 10.2307/j.ctv6gqrgx

R Core Team (2021) *R: A Language and Environment for Statistical Computing.* Available at: https://www.r-project.org/.

Riva, F., and Fahrig, L. (2022). The disproportionately high value of small patches for biodiversity conservation. *Conserv. Lett.* 15, e12881. doi: 10.1111/CONL.12881

Robbins, M. M., Gray, M., Fawcett, K. A., Nutter, F. B., Uwingeli, P., Mburanumwe, I., et al. (2011). Extreme conservation leads to recovery of the virunga mountain gorillas. *PloS One* 6, e19788. doi: 10.1371/journal.pone.0019788

Roberson, L. A., Beyer, H. L., O'Hara, C., Watson, J. E. M., Dunn, D. C., Halpern, B. S., et al. (2021). Multinational coordination required for conservation of over 90% of marine species. *Glob. Change Biol.* 27, 6206–6216. doi: 10.1111/gcb.15844

Runting, R. K., Meijaard, E., Abram, N. K., Wells, J. A., Gaveau, D. L. A., Ancrenaz, M., et al. (2015). Alternative futures for Borneo show the value of integrating economic and conservation targets across borders. *Nat. Commun.* 61 (6), 1–11. doi: 10.1038/ncomms7819

SADC (2019). *Southern African Development Community (SADC) Programme for Transfrontier Conservation Areas (TFCAs)* (Gaborone, Botswana:SADC). Available at: https://www.sadc.int/sites/default/files/2022-07/J7625_GIZ_SADC_Programme_for_TFCA_English_High_Res.pdf.

Santini, L., Saura, S., and Rondinini, C. (2016). Connectivity of the global network of protected areas. *Divers. Distrib.* 22, 199–211. doi: 10.1111/ddi.12390

Saura, S., Bertzky, B., Bastin, L., Battistella, L., Mandrici, A., and Dubois, G. (2018). Protected area connectivity: Shortfalls in global targets and country-level priorities. *Biol. Conserv.* 219, 53–67. doi: 10.1016/J.BIOCON.2017.12.020

Schapira, P., Monica, M., Rolkier, G. G., and Bauer, H. (2017). Wildlife migration in Ethiopia and South Sudan longer than 'the longest in Africa': a response to Naidoo et al. *Oryx* 51, 19. doi: 10.1017/S0030605316000363

Schoon, M. (2013). Governance in transboundary conservation: how institutional structure and path dependence matter. *Ashoka Trust Res. Ecol. Environ. Wolters Kluwer India Pvt. Ltd.* 11, 420–428. doi: 10.4103/0972-4923.125758

Senior, R. A., Hill, J. K., and Edwards, D. P. (2019). Global loss of climate connectivity in tropical forests. *Nat. Clim. Change* 98(9), 623–626. doi: 10.1038/s41558-019-0529-2

Simkin, R. D., Seto, K. C., McDonald, R. I., and Jetz, W. (2022). Biodiversity impacts and conservation implications of urban land expansion projected to 2050. *Proc. Natl. Acad. Sci.* 119, e2117297119. doi: 10.1073/pnas.2117297119

Thornton, D., Branch, L., and Murray, D. (2020). Distribution and connectivity of protected areas in the Americas facilitates transboundary conservation. *Ecol. Appl.* 30, 1–10. doi: 10.1002/eap.2027

Thornton, D. H., Wirsing, A. J., Lopez-Gonzalez, C., Squires, J. R., Fisher, S., Larsen, K. W., et al. (2018). Asymmetric cross-border protection of peripheral transboundary species. *Conserv. Lett.* 11, e12430. doi: 10.1111/conl.12430

Trouwborst, A., Fleurke, F., and Dubrulle, J. (2016). Border fences and their impacts on large carnivores, large herbivores and biodiversity: An international wildlife law perspective. *Rev. Eur. Comp. Int. Environ. Law* 25, 291–306. doi: 10.1111/reel.12169

Tshipa, A., Valls-Fox, H., Fritz, H., Collins, K., Sebele, L., Mundy, P., et al. (2017). Partial migration links local surface-water management to large-scale elephant conservation in the world's largest transfrontier conservation area. *Biol. Conserv.* 215, 46–50. doi: 10.1016/J.BIOCON.2017.09.003

Tucker, M. A., Böhning-Gaese, K., Fagan, W. F., Fryxell, J. M., Van Moorter, B., Alberts, S. C., et al. (2018). Moving in the Anthropocene: Global reductions in terrestrial mamMalian movements. *Science* 359, 466–469. doi: 10.1126/science.aam9712

UNEP-WCMC and IUCN (2021). *Protected Planet: The World Database on Protected Areas (WDPA)* (Cambridge, UK: UNEP-WCMC and IUCN). Available at: www.protectedplanet.net [Accessed November 2021].

United Nations General Assembly (2021) *Nature knows no borders: transboundary cooperation – a key factor for biodiversity conservation, restoration and sustainable use.* Available at: https://www.un.org/en/ga/75/resolutions.shtml.

van Hooft, P., Keet, D. F., Brebner, D. K., and Bastos, A. D. S. (2018). Genetic insights into dispersal distance and disperser fitness of African lions (Panthera leo) from the latitudinal extremes of the Kruger National Park, South Africa. *BMC Genet.* 19, 21. doi: 10.1186/s12863-018-0607-x

Vasilijević, M., Zunckel, K., McKinney, M., Erg, B., Schoon, M., and Rosen Michel, T. (2015) *Transboundary conservation: A systematic and integrated approach* (Int. Union Conserv. Nat). Available at: www.iucn.org/pa_guidelines (Accessed April 27, 2023).

Vynne, C., Gosling, J., Maney, C., Dinerstein, E., Lee, A. T. L., Burgess, N. D., et al. (2022). An ecoregion-based approach to restoring the world's intact large mammal assemblages. *Ecography (Cop.)* 2022. doi: 10.1111/ECOG.06098

Wall, J., Wittemyer, G., Klinkenberg, B., LeMay, V., Blake, S., Strindberg, S., et al. (2021). Human footprint and protected areas shape elephant range across Africa. *Curr. Biol.* 31, 2437–2445.e4. doi: 10.1016/J.CUB.2021.03.042

Wegmann, M., Santini, L., Leutner, B., Safi, K., Rocchini, D., Bevanda, M., et al. (2014). Role of African protected areas in maintaining connectivity for large mammals. *Philos. Trans. R. Soc B Biol. Sci.* 369, 20130193. doi: 10.1098/RSTB.2013.0193

Williams, D. R., Rondinini, C., and Tilman, D. (2022a). Global protected areas seem insufficient to safeguard half of the world's mammals from human-induced extinction. *Proc. Natl. Acad. Sci.* 119, e2200118119. doi: 10.1073/pnas.2200118119

Williams, D. R., Rondinini, C., and Tilman, D. (2022b). Global protected areas seem insufficient to safeguard half of the world's mammals from human-induced extinction. *Proc. Natl. Acad. Sci.* 119, e2200118119. doi: 10.1073/pnas.2200118119

Zbicz, D. C. (2003). Imposing transboundary conservation. *J. Sustain. For.* 17, 21–37. doi: 10.1300/J091v17n01_03