Remote sensing of wildlife connectivity networks and priority locations for conservation in the Southern Agricultural Growth Corridor (SAGCOT) in Tanzania

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Abstract

Land conversion is causing habitat loss and fragmentation worldwide, particularly in Africa, where the proliferation of agricultural development corridors may threaten vital areas for ecological connectivity and wildlife survival. To conserve connectivity, careful landscape planning is necessary, which strongly relies on remotely sensed land cover maps. Here, we present a remote sensing-based framework that efficiently identifies priority locations for connectivity conservation. We applied the framework in the Kilombero catchment and development cluster of the Southern Agricultural Growth Corridor (SAGCOT) in Tanzania, where new agricultural development projects could act as barriers for connectivity. Using satellite imagery from Sentinel-1 and 2, we mapped the mixture of mountain and lowland land covers and habitats with an overall accuracy of 75%. Then, we assessed ecological connectivity to predict African elephant corridors and prioritize them in two ways. First, we identified elephant corridors that contribute the most to current landscape connectivity, and second, we identified those whose restoration would significantly enhance landscape functionality and improve the current connectivity level. We mapped 214 potential elephant corridors, identified 43 of them as priority for conservation, and 43 as targets for restoration. Our model predicted four already known corridor areas in and around the Kilombero valley floodplain, and other important corridors not yet identified by previous studies in the south of the basin. Priority elephant corridors inside the floodplain showed narrow widths and low permeability, indicating low functionality in the connectivity network. Nevertheless, the abundance of priority corridors for restoration suggests that connectivity could be recovered if the recommended measures are applied during SAGCOT planning and implementation process. Our findings demonstrate the possibilities of combining multispectral and radar data for guiding biodiversity management in development corridors and for assessing ecological connectivity worldwide.

Introduction

Africa is experiencing an unprecedented proliferation of development projects that may threaten high biodiversity areas (Laurance et al., 2017; Laurance et al., 2015). These projects often belong to development corridors, such as the Southern Agricultural Growth Corridor of Tanzania (SAGCOT), which is a public-private partnership aimed...
to enhance agricultural productivity, food security and livelihoods. SAGCOT is planned to be fully implemented by 2030 in southern Tanzania through “clusters”, which are six geographical concentrations of farmers, agribusinesses and service providers (SAGCOT, 2017). One of them, still in the planning phase, will be implemented in the Kilombero valley, which hosts one of the biggest freshwater wetlands in East Africa (Wilson et al., 2017). The site is crucial for biodiversity conservation being home to endangered species and species refuge during the dry season. Elephants and other large mammals use the floodplain as a corridor between the neighbouring wildlife areas (Wilson et al., 2017). Consequently, previous studies investigated the conservation status of its connectivity networks highlighting nationally important corridors such as Ruipa, Nyanganje, Mwanihana-Magombera and Mngeta (Fig. 1; Jones et al., 2012; Jones et al., 2009; Riggio & Caro, 2017; Rovero & Jones, 2012).

This landscape has been a magnet for infrastructure development, resettlement, immigration and farming expansion over the last 50 years (Monson, 2009). This increase in population, pastoralism and agricultural land has led to habitat loss, fragmentation, and wildlife populations decline (Bonnington et al., 2007; Seki et al., 2018), especially in the floodplain where wetlands are being transformed into croplands (Munishi & Jewitt, 2019; Thonfeld et al., 2020a, 2020b). Subsequently, pre-existing landscape connectivity has been compromised (Leemhuis et al., 2017), threatening the functionality of the connectivity network (Jones et al., 2012; Jones et al., 2009). A careful choice of the expansion areas for agriculture, tree plantations and infrastructure will be required to minimize wildlife corridor degradation, avoiding the isolation of wildlife populations and maintaining ecosystem functioning (Fynn & Bonyongo, 2011; Newmark, 1996).

Accordingly, the United Republic of Tanzania (2018) recently gazetted the regulations for the legal designation of wildlife corridors as protected areas. For this purpose, connectivity assessments can provide spatially explicit information about the most important landscape elements to conserve (Saura & Pascual-Hortal, 2007), so that connectivity networks can be intelligently planned in a landscape matrix with increasing human pressure (Fynn & Bonyongo, 2011; Newmark, 2008).

Graph theory combined with the habitat availability concept is a widely embraced approach to assess connectivity aiming to support management decisions (De la Fuente et al., 2018; Dondina et al., 2018; Gurrutxaga et al., 2011; Saura et al., 2017; Schivo et al., 2020). Graphs are data structures composed of nodes (suitable habitat units surrounded by inhabitable land) and links (potential connections between nodes) that allow simple but effective representations of the landscape to conduct complex connectivity analyses (Adriaensen et al., 2003; Bunn et al., 2000; Saura & Torne, 2009). Moreover, the habitat availability concept is important to coordinate landscape connectivity with other conservation planning purposes since it considers that connectivity occurs within habitat patches and because of the connections between them (Pascual-Hortal & Saura, 2006).

Based on the graph theory and habitat availability approaches, several indexes have been developed to assess landscape connectivity. These indexes can identify essential landscape components by calculating the difference in connectivity values between a situation in which a landscape element is present, and a hypothetical one in which this element is modified or removed. Therefore, wildlife corridors that contribute more to overall connectivity can be identified (Saura & Pascual-Hortal, 2007).

Links, which ultimately represent wildlife corridors, can be defined using euclidean or preferably effective distances (cost-weighted), which consider species responses towards the landscape. In the latter, distances are weighted to take into account the costs for a species of moving through the land covers between nodes (Adriaensen et al., 2003; Saura & Pascual-Hortal, 2007). Movement costs are obtained from resistance surfaces, which are spatial layers whose pixels have a resistance to movement value, with low values belonging to permeable land covers to movement and vice versa (Mateo-Sánchez et al., 2015; Zeller et al., 2012). Therefore, land cover is a frequent environmental variable to estimate resistance surfaces (De La Fuente et al., 2018; Zeller et al., 2012).

In recent connectivity studies, satellite remote sensing is becoming increasingly common to map land cover (Bergl et al., 2012; Bleyhl et al., 2017; Osipova et al., 2018, 2019a). Satellite imagery, and particularly Sentinel-1 and 2 imagery from the ESA Copernicus programme, has great potential to produce accurate land cover classifications (Lopes et al., 2020; Mercier et al., 2019). Besides being open access, Sentinel data offers high spatial resolution and a high revisit time. Moreover, Sentinel-2 has three red-edge spectral bands which provide additional information for mapping vegetation (Forkuor et al., 2018). Sentinel-1 backscatter data are not affected by cloud conditions (Clerici et al., 2017) and can also be used to accurately map land cover, especially if dual polarization data are combined (Abdikan et al., 2016). Despite the current possibilities for mapping land cover, the Kilombero catchment lacks detailed and comprehensive spatial information about connectivity. To address this issue, we combined Sentinel-1 and 2 imagery to map land cover and habitat types and identify priority corridors (top 20% with the highest overall importance for connectivity) to protect and restore ecological connectivity.
We tested this framework selecting the African elephant (*Loxodonta africana*) as the focal species due to three reasons. First, elephant corridors play a key role in the long-term viability of other wildlife (Roever et al., 2013). As elephants require considerable space and have been suggested as a reliable focal species for connectivity planning in similar landscapes, their corridors may be suitable for other large terrestrial mammals in the study area (Epps et al., 2011). Second, there is a wide availability of literature for this species, which allows for a comprehensive connectivity analysis. And third, because this landscape is essential for elephant connectivity between two important populations in Tanzania (Debonnet & Nindi, 2017). In this way, we assessed connectivity from a functional perspective, which has never been applied in the Kilombero catchment.

The results of this study provide higher detail of wildlife corridors to accurately identify strategic locations to protect and restore ecological connectivity. Thus, the forthcoming development projects of SAGCOT can be planned so that potential impacts on connectivity are avoided or minimized. Finally, we discuss the implications of our results in the Kilombero cluster and the applicability of this framework more widely.

**Materials and Methods**

The identification of priority locations for elephant connectivity involved three steps: (1) A high-resolution land cover and habitat classification for the study area (see Data S1 for study area details); (2) an accurate identification of wildlife corridors; and (3) a prioritization of locations for connectivity conservation actions.

**Land cover and habitat classification**

Following the workflow in Figure 2, we developed a land cover map of 20 metres resolution from two Sentinel-1 and 2 cloud-free image composites for the period 2017-2018 and GEO Wetlands Community portal (SWOS, 2018) layers. The Sentinel-2 composite was created in Google Earth Engine (GEE) using the median top of
atmosphere reflectance values (level-1C). Clouds were masked using the quality band (ESA, 2012), and cloud shadows were masked using azimuth and zenith angles to estimate the position of the shadow (Muro et al., 2020). The Sentinel-1 composite was created as well in GEE using the percentiles 05, 50 and 99 as representative of the maxima, median and minima backscatter responses through the study period. Sentinel-1 imagery is offered already pre-processed in GEE and details about it can be found in GEE (2020). We used Red-Edge, NIR and SWIR information from Sentinel-2 offered in 20 m resolution and therefore opted for a 20 m resolution, even if some bands are available in 10 m resolution.

We performed a classification of the main land covers, followed by a sub-classification of the tree-covered areas. We applied Random Forest as the classification algorithm and set it at 1000 trees in both cases. The RF classifier is an ensemble classifier that generates multiple decision trees to determine the probability of the class membership (Belgiu & Drăguț, 2016). For full details of the land cover map procedure, see SM2. The resulting land cover map included a total of 12 land cover classes which include (1) Moist Forest, (2) Dry Forest, (3) Tree Plantation, (4) Shrub cover/Natural Mosaic, (5) Grassland, (6) Crop-lands, (7) Wetlands, (8) Urban Areas, (9) Open Water, (10) Large-scale Crops, (11) Railways and (12) Roads. We used the guidelines developed by FAO (2016) and Olofsson et al., (2013, 2014) to design the classification accuracy assessment, and obtain error-adjusted area estimates of the land cover classes.

Based on the land cover map, we developed a habitat map according to International Union for Conservation of Nature (IUCN) Habitat Classification Scheme version 3.1 (IUCN Red List, 2012). We used a crosswalk table that relates European Space Agency (ESA) Climate Change Initiative (CCI) land cover classes to IUCN Level 2 habitat types, to reclassify the land covers into habitat types. To effectively map habitat types, we also used ancillary geo-spatial datasets (SM2 for details).

**Identification of wildlife corridors**

To design the African elephant connectivity analysis, we used the graph theory approach (Bunn et al., 2000). We selected as nodes the protected patches of suitable habitat for elephants where there is evidence of their presence (SM3 for details). We disregarded habitat patches that were smaller than 30 ha since this value ensures a sufficient area for elephants to use as stepping stones while dispersing through the landscape (J. Mwalugelo, pers. comm.). Ultimately, patches that were closer than 250 m to each other were aggregated and considered as one. We assigned values of resistance to elephant movement to the different land cover and habitat types based on those...
given by Van de Perre et al. (2014). We adapted these values to match the thematic resolution of this study according to fieldwork experience (Table 1). We also conducted a sensitivity analysis to address potential uncertainties from the selected resistance values (SM4).

We defined the links using least-cost modelling (Adriansen et al. 2003). This approach estimates the single path between two nodes that implies the minimum effective distance. Therefore, least-cost paths have the most permeability and the highest probability of being used by dispersing animals (Larkin et al., 2004; LaRue & Nielsen, 2008). To inform about the corridor width associated to each link, we calculated the normalized-corridors surface. Each pixel of this surface reflects how much more cost a suboptimal path that uses that cell would take as compared to the least-cost path. We also obtained the cost-weighted distance to least-cost path length ratio for every link. We computed least-cost paths, effective distances and the normalized-corridors surface using the Linkage Mapper software (McRae & Kavanagh, 2011).

### Priority locations for connectivity conservation actions

Once the corridors were mapped, we identified those critical for connectivity and that should receive priority conservation measures using two criteria: (1) currently important corridors to connectivity, as those that contribute most to maintaining dispersal flows and whose blockage would mean a severe degradation in the functionality of landscape connectivity; and (2) restoration corridors, whose restoration would mean a significant improvement in the overall connectivity. For this, we used the probability of connectivity (PC) index (based on the habitat availability and graph theory approaches), which indicates to which extent two nodes are connected based on the probability of individuals to cross from one to another (for further details see Saura & Pascual-Hortal, 2007). To calculate the PC, we used the median dispersal distance to indicate a probability of 0.5 for an individual to cross between nodes that are at that distance. Based on a home range size of 328 km² (Hofer et al., 2004) and the formula (Fig. S1) established by Bowman et al. (2002), we estimated the median dispersal distance of elephants in 127 km. We multiplied this value by the mean resistance of the map (10.11) to get the median dispersal effective distance. To account for potential uncertainty in dispersal estimates and test the robustness of our findings, we also estimated elephant dispersal distances through the formula relying on mammal body mass and diet type (Sutherland et al. 2000), and separating female and male dispersal abilities (see SM5). Unless otherwise stated all results described next refer to the dispersal distance abovementioned.

To identify the currently important corridors, we analysed the impact of removing each link to check their contribution to overall connectivity by calculating the difference in PC ($dPC_{\text{con}}$). To identify the restoration corridors, we measured the increase in overall connectivity ($dPC_{\text{rest}}$) resulting from a hypothetical situation in which each link was restored to be fully composed of suitable habitat – i.e. being its effective distance equal to its length and offering minimum resistance. For computing the $dPC$ values, we used the Conefor software (Saura & Torne, 2009) and their Link Removal and Change functions. Next, we selected the links with the top 20% $dPC_{\text{con}}$ values to prioritize the corridors that are currently most important for connectivity (i.e. corridors to be protected). Likewise, we selected the top 20% $dPC_{\text{rest}}$ links to prioritize the corridors where it would be most beneficial to apply restoration measures (i.e. corridors to be

**Table 1. Elephant resistance to movement values according to habitat type or land cover class.**

| Habitat or land cover | Resistance | Class from Van de Perre et al. (2014) |
|-----------------------|------------|--------------------------------------|
| Dry savanna           | 1          | Open Forest.                         |
| Tropical Moist Lowland Forest; | 5          | Woody: Analogous to dry forest.      |
| Tropical Moist Lowland Forest; | 5          | Closed and Evergreen Forest: Analogous to moist forest. |
| Tropical Dry Shrubland | 5          | Natural shrub.                       |
| Tropical Dry Lowland Grassland | 5          | Grassland.                           |
| Shrub Dominated Wetlands; | 5          | Marsh (shrub): for wetlands with shrub cover. |
| Tropical Seasonally Flooded Lowland Grassland; | 5          | Open marsh: Assigned to the rest of wetland habitats present in the Kilombero floodplain (SF3). |
| Bogs, Marshes, Swamps, Fens, Peatlands | 20      | Crop: Plantations are assigned the same value due to their human land use. |
| Arable Land; Plantations | 20      | Trail.                               |
| Trails                | 20         | Permanent and Seasonal river: Common value of the two classes. |
| Irrigated land        | 100        | Crop (rice): Assigned for intensive agriculture (e.g. rice is grown in Mngeta intensive farm). |
| Urban Area; Rural Gardens; Water storage areas Main Roads; Railroads | 500   | Urban: Same value for gardens and water storage areas due to their high human use. |
|                       |            | Main road. Railroads considered similar. |

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restored). Last, we considered the required intensity of the restoration actions and we identified among priority corridors for restoration those with a higher potential contribution to connectivity in relation to the restoration cost required. As in SF6, we divided the dPC_{rest} value (dPC_{norm-rest}) by the difference between the current effective distance and the effective distance if the corridor was restored (equal to corridor length).

**Results**

The land cover classification yielded an overall accuracy of 75.34% while the "Tree Cover" subclassification achieved an accuracy of 86.88%. For Sentinel-1, the most powerful predictors were texture metrics (2 layers) and the 05 percentiles of both polarizations. For Sentinel-2 these were the NDVI and the Red and SWIR-2 bands. From the ancillary datasets, the best predictor was the GEO-Wetlands Potential Wetland Areas. The NDMI index and the Sentinel-2 Red and SWIR layers were the most important in the subclassification (Fig. 3). See Table S1 for the confusion matrix of the land cover classification.

Error adjusted area estimates (ST2) showed "Shrub cover/Natural mosaic" as the most extensive, followed by "Tree covered" areas. Among the tree-covered classes "Dry forests" was the class covering the largest area (see SF2 for the land cover map). A total of 77.18% of the catchment was composed of natural habitats (SF3 for the habitat map). Arable lands occupied a 19.50% of the catchment, mostly located in the south-west of the catchment and across the floodplain.

Potential habitat types for elephants comprised an area of 24 214 km² (60.15% of the map area). Most was dry savanna, which was also the dominant habitat in the catchment (35.16%). Suitable habitats for elephants were distributed across Selous Game Reserve (GR; in which the new Nyerere National Park has been established), and to the southwest of the catchment (Fig. 4 and Fig. S4). Suitable habitat also showed in the Udzungwa and Mngeta ecosystems, where moist and dry forests were abundant, and in small forested habitat patches inside the floodplain. An area of 7774 km² (32.11% of the suitable habitats for elephants) was selected as habitat patches to model connectivity according to the criteria described above.

Corridors were distributed across the east half of the study area, mainly in the floodplain and connecting it with the surrounding habitat patches. Corridors with narrower permeable widths concentrated in the north of the floodplain, where the links had the highest cost to path length ratios. Wider corridors were identified in the core of the floodplain and in the south. We identified 214 potential corridors among elephant habitat areas inside the Kilombero landscape (Fig. 4).

Sixty-seven corridors were identified as priority, with 24 of them as priority to be protected, 24 to be restored, and 19 for both cases. This made a total of 43 priority corridors to be protected and 43 to be restored. Priority corridors only to be protected had nearly 95% (ST3) of their trajectories going through natural areas. Conversely, priority corridors only to be restored showed 28% of their trajectories composed of croplands and 72% of natural areas. Many priority links belong (or partially belong) to the four corridors areas highlighted by previous studies (Jones et al., 2012; Jones et al., 2009; Rovero & Jones, 2012) revealing precise routes that elephants may use to move between habitat areas. Priority links to receive restoration measures were generally located in the north of the floodplain, on extensively cultivated areas such as those in Mwanihana-Magombera (Fig. 5A: MM1 and MM3), Nyanganje (Fig. 5B: Ny3), and Ruipa (Fig. 5C: R3). Those present in Mwanihana-Magombera and Nyanganje corridors (Fig. 7: MM1, MM3 and Ny3) may require lower restoration efforts. Priority links to be protected were predicted on natural covers, such as those in Mngeta (Fig. 5C: Mn1 and Mn2). Another example are the priority corridors connecting the Ngapemba wetlands (Fig. 6: Ng1 and Ng2). Multiple links operating through and around the south of the floodplain show that elephants might have more alternatives to cross between the Selous GR and Udzungwa Mountains than previously considered. Other corridors were also found connecting the Kilombero RS with the Selous GR and the Mbarangan’du WMA through more isolated areas that conservationists might have overlooked (Fig. 6 and Fig. S5).

Results for the estimation of alternative resistances scenarios showed strong correlations between their corridor surfaces (SM4). Besides, the different dispersal distances explored resulted in the same set of priority corridors (SM5).

**Discussion**

We identified 43 priority elephant corridors to be protected and 43 to be restored in the Kilombero catchment by following a theoretical framework that uses open access Sentinel imagery. The high spatial resolution of the corridors makes our results a robust and detailed source of spatially explicit information to identify areas of high priority for elephant connectivity in the Kilombero SAGCOT cluster.

**Land cover and habitat classification**

Previous studies have explored the combination of multispectral and radar data with good results (Carrascos et al., 2019; Clerici et al., 2017; Mercier et al., 2019; Muro et al., 2020). The combination of both types of sensors has
permitted us to obtain a good classification accuracy for such a heterogeneous landscape. Sentinel-1 data and the derived texture metrics were fundamental to identify wetlands, and Sentinel-2 data and derived indices (e.g. NDVI, NDMI) played a key role in the classification of vegetation and later in the subclassification of forest types with high accuracy (Fig. 3).

Although there are already several remote sensing-based studies investigating the landscape and ecosystems of Kilombero (Muro et al., 2018; Riggio & Caro, 2017; Thonfeld et al., 2020a, 2020b), ours is the first one that provides habitat and connectivity maps at a thematic and spatial resolution suitable to predict elephant corridors. The use of multitemporal metrics improves the classification capacities since it captures the different stages of dynamic habitats (Muro et al., 2020; Oeser et al., 2020). Other studies have used maxima and median metrics from optical data (e.g. Muro et al., 2020). However, the dense cloud cover of Kilombero created too much noise when computing maxima and minima metrics. Here, Sentinel-1 was instrumental to cover the rainy periods and the floodplain dynamics since it is not affected by cloud conditions.

Continuous satellite imagery provides the only viable means of long-term and global monitoring of ecosystems and biodiversity (Pettorelli et al., 2016; Skidmore et al., 2015). Therefore, the availability of archive and recent free satellite imagery from radar and optical sensors is essential for conservationists worldwide with restricted budgets to still produce results ready for decision making. Our results also support the wider use of Sentinel-1 and 2 data along with open geospatial datasets for guiding nature management worldwide. Thus, we advocate for their potential for mapping and assessing wildlife connectivity.

Including ancillary information (i.e. the GEO Wetlands Community portal (SWOS, 2018) datasets) in addition to the spectral information improved classification accuracies and thematic resolutions in our case, as well as in other studies (Manandhar et al., 2009; Muro et al. 2020; Na et al., 2009). The Potential Wetland Areas layer was key for the performance of the classifier. This layer has been produced using the digital elevation model from Shuttle Radar Topography Mission (SRTM). Thus, we did not include the SRTM directly in the classification to avoid redundancy.
Identification of wildlife corridors

We present a comprehensive approach to map functional connectivity that ensures a fine-scale representation of all the features of the landscape, in comparison to the less systematic approaches (Jones et al., 2009) and broader scales (1 km; Riggio & Caro, 2017) of previous studies in Tanzania.

Nevertheless, our results present some limitations worth mentioning. Empirical occurrence or movement data would be preferable to obtain, improve or corroborate landscape resistance and movement ability, but these data were lacking for elephants in the study area. This is a widespread issue in connectivity studies that favours the use of expert opinion in the literature (Zeller et al., 2012). Additionally, considering human tolerance or other anthropogenic factors may be relevant for estimating resistance surfaces to represent better how human behaviour influences elephant movement (Ghoddousi et al., 2021).

We used least-cost modelling to map links as it is a common connectivity approach for studying connectivity (Beier et al., 2008; De La Fuente et al., 2018). However, it is important to clarify that least-cost paths do not represent the route that species are always going to take, but the single route with the greatest potential of being used according to low dispersal efforts and mortalities (LaRue & Nielsen, 2008). Actual paths taken will imperfectly follow these routes because of animal stochastic behavioural choices (Cushman et al., 2010). We recommend that conservationists consider permeable corridor widths (Fig. 4) rather than optimal routes alone, to include the areas associated with each link that would not imply greater travel costs (McRae & Kavanagh, 2011). Accordingly, narrow corridors should receive special attention since these represent bottlenecks in the connectivity network, meaning that even slight changes in their land covers would lead to their total blockage (De la Fuente et al., 2018).

Fieldwork and ground-truthing should also be conducted to verify the current use of a predicted corridor. This can be done using animal movement data collected via VHF (Very High Frequency) or GPS collars (Bond et al., 2017; Zeller et al., 2012) or animal density estimates obtained by field counts (Kiffner et al., 2016; Osipova et al., 2019b), although less costly alternatives such as...
Figure 5. (A) Mwanihana-Magombera, (B) Nyanganje, (C) Mngeta (left) and Ruipa wildlife corridors’ priority links. See Figure S5 for maps of the entire study area.
Interviewing people living within or adjacent to corridors can also provide accurate information on wildlife movements (Riggio & Caro, 2017). Other more random approaches which model several routes, including suboptimal ones, are also available - i.e. circuit theory. Nevertheless, it is not always possible to apply conservation actions in multiple corridors simultaneously as these measures are usually expensive. Under these circumstances, predicting optimal routes using least-cost modelling can be the most efficient and pragmatic alternative (De la Fuente et al., 2018).

**Priority locations for connectivity conservation actions**

Our results can be used to identify locations for new development projects where potential impacts to connectivity are minimized and avoid areas of importance for connectivity. This is especially relevant now that SAGCOT projects will promote agricultural developments and modern linear infrastructure that could act as dispersal barriers (Van de Perre et al., 2014). These results could also be useful when planning mitigation or restoration measures (e.g. linear infrastructure crossing points) in already designed development projects to reduce or avoid potential impacts over wildlife corridors without compromising socio-economic development. Furthermore, this prioritization can help to allocate the often-limited resources for conservation in an efficient and ecologically sound way.

Based on the results, we used available literature to recommend and discuss two types of conservation actions for elephant connectivity. First, protection actions such as the creation of protected areas or other management that ensure long term viability of the priority corridors. Second, restoration actions, which aim to recover a functional corridor network and are principally proposed for restoration priority corridors.

**Protection of corridors**

The priority links identified in the formerly known corridor areas support their fundamental role in the region’s connectivity. However, only some corridors remain functional due to natural land conversion (Jones et al., 2012).
Amongst the best preserved are the links of the Mngeta corridor due to low human presence and a slightly damaged natural environment (Museo Tridentino di Scienze Naturali, 2007). However, the proximity of Mngeta village and a road in the southern border are resulting in new encroachments (Rovero & Jones, 2012), suggesting that the corridor should promptly be protected. The accurate location of the two priority links (Fig. 5C: Mn1 and Mn2) could guide conservation efforts inside the corridor, such as the creation of a Forest Reserve or the attempt to merge Kilombero and Uzungwa Scarp Nature Reserves by incorporating the Mngeta corridor (Rovero & Jones, 2012).

Other priority corridors for the elephant connectivity were predicted in more degraded areas. For instance, those located over farmlands in the Mwanihana-Magombera corridor. However, croplands only act as semi permeable barriers for crossing elephants (Riggio & Caro, 2017). Therefore, Mwanihana-Magombera is currently the only viable corridor for elephants between the Udzungwa and the Selous, due to the degradation and blockage of Ruipa and Nyanganje corridors (Debonnet & Nindi, 2017; Jones et al., 2012). With the imminent development brought by SAGCOT, urgent protection of their two links (Fig. 5A: MM1 and MM3) is necessary to ensure elephant connectivity between both ecosystems. Conservation efforts should be first taken on the north link (MM1) due to its shorter length and its importance for connectivity. For its protection, an appropriate alternative could be the creation of a formal wildlife corridor (United Republic of Tanzania, 2018) through cooperation between communities, NGOs and protected area authorities.

We also predicted important corridors in the Kilombero floodplain, such as those connecting the Ngapemba wetlands with the surrounding habitats. Therefore, Ngapemba wetlands...
wetlands should also be considered a strategic element for connectivity. A recent assessment of the area status found that elephant and other large mammal species still inhabit these wetlands despite increasing land pressure (Mombo et al. 2018). Ngapemba wetlands could be included in the Kilombero Game Controlled Area (GCA), taking advantage of the new planned delineation of its borders to ensure future protection of remaining natural habitats (A. Mtui, pers.comm.). However, the Kilombero GCA has been ineffective ensuring habitat conservation inside its boundaries due to encroachments and conversion to agriculture or grazing land (Wilson et al., 2017). Improvements in the management plan are needed to achieve a proper integration of the land uses without disregarding habitat protection (Wilson et al., 2017).

**Restoration of corridors**

Corridors predicted in the north of the floodplain generally show narrow permeable widths and high movement costs for their length, which relates to low corridor quality (Bleyhl et al., 2017), supporting the lack of functionality inside the Nyanganje and Ruipa corridors (Jones et al., 2012). However, in Ruipa, elephants still attempt to cross, especially from its eastern part, which suggests that the corridor could be reopened (Jones et al., 2012). Our results showed many restoration priority corridors, indicating that restoration could bring connectivity back into function linking vital areas for conservation (Jones et al., 2012; Riggio & Caro, 2017). These could be done effectively through reforestation with native species that are food source for elephants and improving the water availability in the dry season (Parren & Sam, 2003). These measures are especially recommended for Nyanganje and Mwanihana-Magombera corridors (Fig. 7: MM1, MM3 and Ny3) since lower restoration efforts in relation to potential benefits for connectivity would be needed.

**Conclusion**

We present a spatially explicit framework to map wildlife corridors and prioritize strategic locations to protect and restore ecological connectivity. The framework combines freely available satellite imagery and other spatial data, and we applied it to map elephant corridors in the Kilombero catchment. Our results matched known corridor locations and revealed potential new corridors. Moreover, our findings can support the spatial planning of new projects, and conservation and mitigation measures in the SAGCOT. Besides mapping a precise distribution of the potential corridors, these can be prioritized according to their contribution to the overall landscape connectivity, and according to their connectivity potential after restoration. The approach can also be reproduced in other contexts, regions and for other species in need of conservation. Especially, it can support the expected developing agricultural projects from low and middle-income countries by providing ready to use information for an informed decision making.

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**Data Availability Statement**

Results including land cover, habitat and connectivity layers are available in the Development Corridors Partnership data portal: https://dcp-uneq-wcmc.opendata.arcgis.com/. The imagery can be processed with the free and open-source EnMAP-Box software: https://www.enmap.org/data_tools/enmapbox/.

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**Supporting Information**

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

**Data S1.** Supplementary Methods, Tables and Figures 1 and 6.

**Figure S2.** Land Cover Map of the Kilombero catchment.

**Figure S3.** Habitat Map of the Kilombero catchment. The map was obtained by applying a crosswalk table.

**Figure S4.** Resistance surface for elephant movement inside the Kilombero catchment. In dark green, the estimated elephant.

**Figure S5.** Priority corridors to be protected according to their contribution to connectivity (red) and/or to be restored according to their potential contribution to connectivity if restored (pink).