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TECHNICAL NOTE

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An AI-based platform to investigate African large carnivore dispersal and demography across broad landscapes: A case study and future directions using African wild dogs

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Abstract

Understanding dispersal patterns and demographic processes is crucial for the development of evidence-based conservation practices. Obtaining such information relies on the ability to identify and track individuals across spatial and temporal scales relevant to the life-history events under investigation. This knowledge can be achieved by combining photographic and sighting data collected by various sources with a high accuracy automated individual identification platform. Here, we present the African Carnivore Wildbook (ACW), an AI-based graphical user interface tool capable of identifying individuals of several African carnivore species and specifically developed to accommodate the above outlined needs. We showcase the ACW functionality using the endangered African wild dog as an example. Pictures collected over an area >56,000 km^2 and submitted to ACW allowed inferences on movement patterns and dispersal at regional and international scales; for instance, transboundary dispersal events >200 km were documented. ACW furthermore enabled monitoring some individuals for >4 years; such information is invaluable for reliable survival analyses. We discuss how the ACW can contribute to data collection at appropriate spatial and temporal scales to support population monitoring, scientific research and management of African wild dogs and other apex carnivores and to the conservation of these charismatic species.

KEYWORDS
African Carnivore Wildbook, citizen science, HotSpotter, inter-institutional collaboration, Kavango-Zambesi Transfrontier Conservation Area, long-distance dispersal, open source, pattern identification algorithm, transboundary, wildlife

Résumé

Le développement de pratiques de conservation fondées sur des données probantes passe par la compréhension des schémas de dispersion et des processus démographiques. L'obtention de ces informations repose sur la capacité d'identifier et de suivre les individus sur des échelles spatiales et temporelles correspondant aux événements de l'histoire de la vie étudiés. Ces connaissances peuvent être acquises en combinant les données photographiques et d'observation recueillies par diverses sources avec une plate-forme d'identification individuelle automatisée de haute précision. Le présent document présente l'*African Carnivore Wildbook* (ACW), un outil d'interface utilisateur graphique basé sur l'IA, capable d'identifier les individus de plusieurs espèces de carnivores africains et spécifiquement développé pour répondre aux besoins décrits ci-dessus. La fonctionnalité de l'ACW est illustrée par l'exemple du dingo africain, une espèce en voie de disparition. Grâce aux images collectées sur une zone de plus de 56 000 km2 et soumises à l'ACW, il a été possible de déduire des schémas de déplacement et de dispersion à l'échelle régionale et internationale; par exemple, des événements de dispersion transfrontalière de plus de 200 km ont été documentés. En outre, l'ACW a permis de suivre certains individus pendant plus de 4 ans; ces informations sont inestimables pour des analyses de survie fiables. Nous examinons les possibilités de contribution de l'ACW à la collecte de données à des échelles spatiales et temporelles appropriées pour soutenir le suivi des populations, la recherche scientifique et la gestion des dingos africains et d'autres carnivores de premier plan, ainsi que la conservation de ces espèces charismatiques.

1 | INTRODUCTION

Our ability to individually recognise and follow the fate of single individuals throughout their lifetime is crucial for answering key ecological and conservation questions. These questions include aspects such as occupancy, survival, movement and dispersal, reproductive success and are crucial for modelling populations where all individuals are considered explicitly (e.g. Clutton-Brock & Scheldon, 2020; Matthiopoulos et al., 2015). However, following single individuals of wide-ranging species is particularly challenging as they might move to areas that are difficult to access, disperse out of the range of research of single institutions (typically delineated by a relatively small and well-defined study area) or even cross-political borders (Cozzi et al., 2020). Advancing and integrating a technological solution that overcomes these limitations is of utmost importance for extending our ecological inferences to broader spatial and temporal extents that accurately reflect the natural scale of the processes being studied.

Several methods have been used for monitoring population trends and life-history processes such as dispersal and movement patterns. For instance, GPS tags have proven effective in following the movements and fate (e.g. survival) of single individuals (Cagnacci et al., 2010). Despite providing precise information regarding an animal's location and movement patterns, they have some major limitations. First, the battery life of these tags is typically much shorter than the lifespan of the tagged individual. Second, financial costs, logistical constraints and technical malfunctions often restrict the number of individuals that are successfully tagged, resulting in inferences that might suffer from a small sample size. Lastly, despite GPS tags fitted with Satellite or GSM technology allow researchers to remotely access the GPS position of the tagged individual, the animal might still be out of reach for the responsible researchers or institutions (e.g. because it moved to a different country).

The use of photographic information from various sources, such as pictures collected by researchers, citizen scientists and tourists has proven a valuable alternative to monitor abundance, occupancy, population trends, and, for individually identifiable species, movement patterns (Araujo et al., 2017; Davies et al., 2013; de Lorm et al., 2023; Marnewick et al., 2014; Schmidt et al., 2023). For instance, Verschueren et al. (2023) used individual identification from images to assess leopard (*Panthera pardus*) and cheetah (*Acinonyx jubatus*) abundance on privately owned farmland in north-central Namibia. Or again, photograph-based individual identification studies have been conducted on cetaceans to assess survival rate, site fidelity and seasonal residence (Zanardelli et al., 2022) However, to fully harness the potential of such data, a freely available, open-source platform that allows collecting, managing, accessing and processing a great amount of data with high accuracy in relatively little time needs to be developed. Without such a centralised and easily accessible platform, data may be stored locally with single researchers, citizen scientists, organisations and individual tourists, thus resulting in scattered and patchy data that is of limited use (MacFadyen et al., 2022).

The African Carnivore Wildbook (ACW; see https://africancarnivore.wildbook.org and Section 2) is a freely available, open-source (https://github.com/WildMeOrg/Wildbook), graphical user interface (GUI) platform specifically developed to accommodate the above needs. Briefly, the ACW consists of a searchable database of timestamped and georeferenced animal images and related metadata that capitalises on the vast photographic information collected by researchers, tourists, citizen scientists and other sources. It is supported by an artificial intelligence-based computer vision pipeline (Parham et al., 2018) that facilitates the detection and recognition of single individuals of the five African large carnivore species, namely African wild dog (*Lycaon pictus*), cheetah, spotted hyaena

(*Crocuta crocuta*), leopard and lion (*Panthera leo*), among other species. ACW individual recognition is possible due to individually distinctive unique coat shadings (African wild dog), dots and spots patterns (cheetah, leopard and spotted hyaena), and facial morphometric features for species without distinct pelage markings (lion). The ACW thus allows obtaining important information about *who* was *where*, *when* and *with whom*, and therefore to address some key life-history traits such as occupancy, survival, movement and dispersal, reproductive success, sociality without temporal and spatial constraints.

The development of such a platform is particularly relevant for studying wide-ranging species such as the African wild dog. Among the African large carnivore species, African wild dogs move and disperse over very large distances and are notoriously difficult to follow (Cozzi et al., 2020; Davies-Mostert et al., 2012; McNutt, 1996); the use of pictures is therefore central to monitoring the movement and the fate of individuals (de Lorm et al., 2023). Single individuals often disappear from a study population, in which case their fate remains unknown. Estimating survival and mortality rates therefore proves difficult (Behr et al., 2023; Hodel et al., 2023). Mean life expectancy for adults individuals that survived the first year of age is 1.9–2.6 years of age depending on sex and circumstances (Behr et al., 2023). Dispersing African wild dogs can cover several hundred kilometres, crossing international borders and moving out of range for single researchers or institutions (Cozzi et al., 2020; Masenga et al., 2016; Sandoval-Seres et al., 2022; Woodroffe et al., 2019). Such long-distance and difficult-to-follow movements primarily take place in well-connected and undisturbed large habitats, such as the Kavango-Zambesi Transfrontier Conservation Area (KAZA/TFCA), which, spanning five southern African countries and >500,000 km^2, represents the world's largest transboundary conservation area (www.kavangozambesi.org).

Here, we present the ACW, a GUI online platform where users can conveniently upload their photographs and relative metadata. We assess the ACW functionality using the example of a free-ranging African wild dog population in the KAZA/TFCA landscape. Specifically, we aimed to investigate whether the ACW can be successfully used to infer long-distance dispersal, directionality of large-scale movements, survival, transboundary movements and group membership and to foster and facilitate inter-institutional information exchange. First, we expected that photograph-based individual identification would allow to detect long-distance dispersal events and directionality akin those reported by means of GPS radio-tracking. Second, given the African wild dog mean life expectancy, we expected re-sighting of individuals to span over several years. Third, we expected that several individuals could be identified at each sighting, thus setting the basis for group membership investigation. Finally, we hope that by showcasing the advantages offered by ACW, we can recruit fellow researchers, citizen scientists and tourists to make use of this platform, thus fostering collaboration and expanding the temporal and spatial scope of ecologically and conservation-relevant questions such as sociality, survival, movement, dispersal and reproductive success.

2 | MATERIALS AND METHODS

2.1 | Study area

We conducted this study across a ca. 150,000 km^2 portion of the Kavango-Zambesi Transfrontier Conservation Area (KAZA/TFCA), including northern Botswana and fractions of adjacent Zimbabwe and Namibia. Despite KAZA/TFCA being officially recognised internationally by official treaties, most of the conservation and research projects on African wild dogs (but also other species) run at the national level, such as the Botswana Predator Conservation (BPC) Program in Botswana, Painted Dog Conservation (PDC) in Zimbabwe, Zambian Carnivore Project (ZCP) in Zambia and Kwando Carnivore Project (KCP) in Namibia. KAZA/TFCA is composed of a mosaic of land uses including protected areas (national parks 32%, game reserves and wildlife management areas 34%, forest reserves 5%), landscapes variously dominated by human enterprises (subsistence agriculture, cattle farming and urban centres 29%) and is home to a large and comparably well-connected African wild dog population (Hofmann et al., 2021, 2023). Movements of few wild dogs across KAZA/TFCA political boundaries have been documented by means of GPS radio collars (Cozzi et al., 2020; Sandoval-Seres et al., 2022). However, due to the relatively small sample size, complementary methods to track movement of individuals are of vital importance.

2.2 | Data collection

The data set is composed of African wild dog pictures and video clips taken opportunistically either by members of African wild dog research organisations, ecotourism companies and tourists between 2017 and 2022 (Figure S1) and uploaded into ACW (see below). To be considered as part of the data set, footage had to at least be associated to a location (GPS coordinates) and a date (YYYY-MM-DD). We used footage taken opportunistically during the day with hand-held devices (i.e. camera and smart phones). We gathered photographic material through three main avenues. We attached posters at the gates of national parks, game reserves and at Maun International Airport advertising the project and asking for wild dog footage and relative metadata; we collaborated with ecotourism companies and advertised the project with leaflets that were accessible to tourists visiting some of the lodges within the study area; we visited some of the lodges in person to inform the guides and the management about the project and the need for wild dog photographs and the related metadata. These methods represented, respectively, roughly 55%, 15% and 30% of the obtained data.

2.3 | African Carnivore Wildbook

The African Carnivore Wildbook (ACW) consists of a database of timestamped and georeferenced images of the five African large

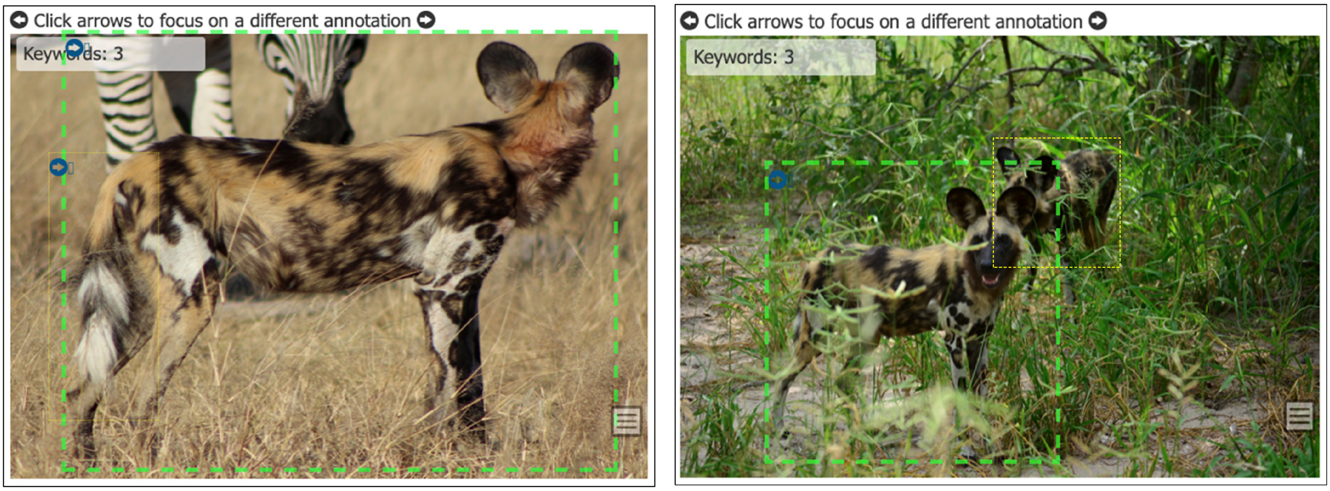

FIGURE 1 During identification, individuals of the species of interest are recognised, and a bounding box (dashed lines) built around each of them. During matching, the target individual (left) is scanned against all individuals presenting a similar viewpoint (i.e. right flank in this case) in the database. Candidate matches (i.e. the dog in the foreground in the right panel) are then confirmed by a human observer.

carnivore species and of brown (Parahyaena *brunnea*) and striped (*Hyaena hyaena*) hyaenas, servals (*Leptailurus serval*), small (*Genetta genetta*) and large (*Genetta tigrina*) spotted genets and African civets (*Civettictis civetta*). It is supported by multiple computer vision algorithms (Crall et al., 2013; Moskvyak et al. 2021; Parham et al., 2018), which speed up and facilitate the identification of single individuals. Since, at the moment, the ACW can only handle pictures and not videos, we extracted still images from video clips at a rate of 1 frame/second using a self-created R script (https://github.com/DavidDHofmann/video2pic). In a nutshell, the identification procedure is composed of four main steps (a detailed guide can be obtained from https://www.t4c.org):

1. *Curation and uploading*: Pictures are manually pre-sorted and curated so that only pictures of the species of interest are uploaded to ACW. Pictures are organised and uploaded in folders, whereby a folder represents a sighting, that is individuals of the same species belonging to the same group (for social species) seen together at a specific location and date. Beside location and date (the very least information), additional metadata such as an animal ID, sex, age and social unit, as well as information about the data owner can be uploaded by the user.
2. *Detection*: The user launches the identification process during which a machine learning-based detector draws a bounding box (Figure 1) around each individual within any given picture. The detection pipeline is a cascade of deep convolutional neural networks and the combined outcomes of each neural network results in an analysed image (for more information see: https://docs.wildme.org/product-docs). A bounding box (with its relative metadata) is referred to as an encounter. Particularly for a social living species such as the African wild dog, a picture may contain several individuals and so several bounding boxes. Bounding boxes can be deleted and created manually in the case of unsatisfactory automatic identification output. This editing capability may be particularly needed in the case of individuals being very close together or laying on each other, as in the case of resting African wild dogs. During initial detection, a viewpoint (e.g. animal left, top-left, right, top-right, etc.) is also inferred by machine learning and automatically assigned to each individual/bounding box.
3. *Matching or Identification*: The user launches the matching process during which the target individual (i.e. the unknown animal that needs to be identified) is matched against all individuals of the same species and similar viewpoint. To speed up and strengthen the matching process, viewpoints of a particular orientation (e.g. left) are only matched against viewpoints of the same or similar (e.g. front-left) orientation. A list of candidate individuals (if any) from the database is associated to the target individuals and is offered to a human expert for validation (Figure 1). A match probability score is associated with each candidate individual. Both detection and matching take place on a server.
4. *Validation*: During the validation process, a human expert confirms or rejects the candidate individuals offered as potential matches under (3). Users can decide how many candidate matches they want the algorithm to offer. To help the human expert in the confirmation or rejection process, the parts of the animal used by the algorithm to identify candidate matches are highlighted by a HotSpotter visualisation (more details are available online).

Most importantly, ACW has been built to ensure that research institutions retain full ownership of all data they upload, while at the same time allowing to match pictures across owners. For instance, if 'organisation A' runs *matching* and one (or more) of the candidate matches are within the pool of pictures of 'organisation B', 'organisation A' will have the possibility to notify via an automatic email 'organisation B' of the positive match. However, unless agreed by 'organisation B', 'organisation A' will not have any access to any of the metadata linked to the matched individual (or any other individuals), and vice versa.

As of January 2023, ACW comprises 50,778 African wild dog encounters (bounding boxes) from different sources and organisations across Africa and 29,741 encounters across the five southern Africa KAZA/TFCA countries. Of these, 25,666 are administered by the Botswana-based BPC. This number is logistically not manageable by human observers. Note that as per January 2023, only approximately 20% of the 25,666 encounters administered by BPC had been run through *identification*, *matching* and *validation*. The below summary statistics (see Section 3) refer to this subset of encounters.

2.4 | Analysis

We report summary statistics on distance and elapsed time between re-sightings of individual wild dogs, number of identified individuals for each sighting and directionality of movement based on re-sightings. We calculated directionality between the first and last sighting of each individual and restricted analysis to individuals that were re-sighted >25 km apart (see the Section 4 for a rational of this cut-off value). To put the above metrics into the appropriate spatial perspective, we calculated the extent of the area covered by the sightings. For this, we used the *kernelUD* function from the *AdehabitatHR* package (Calenge, 2006) in R. We used the default smoothing parameter and calculated the commonly used 90% and 50% utilisation distribution contours (isopleths) with thee *getvertices* function (Calenge, 2006). The 90% isopleth is suitable to describe the overall distribution of the data as it is little sensible to outliers; the 50% isopleth represents the area where the data is concentrated with a 50% probability (Calenge, 2006). We also report on two notable examples of successful between-organisation information transfers that illustrate ACW's potential to promote and encourage its use for information sharing.

3 | RESULTS

From the 25,666 BPC-managed encounters that we ran through *matching* and subsequently *validated*, we could identify 553 individuals across 5 years and 248 sightings. On average, we identified four individuals per sighting (range: 1–31 individuals).

Two hundred and one dogs (36.3% of the total 553 individuals) were re-sighted two or more times, and the maximum and average number of sightings of the same individual were 23 and 1.8, respectively. Maximum and average time elapsed between sightings of the same individual was 4 years and 172 days, respectively. Average relocation distance for individuals re-sighted at least two times was 9.7 km, and the maximum confirmed distance between two sightings of the same individual was 164 km. 60 individuals (10.8% of the total) could be confirmed at locations >25 km apart, suggesting dispersal or exploratory movements (see Section 4 for a justification of this cut-off value).

Sightings were distributed across an area covering roughly 56,000 km^2 (90% isopleth) and three countries, but half of them were

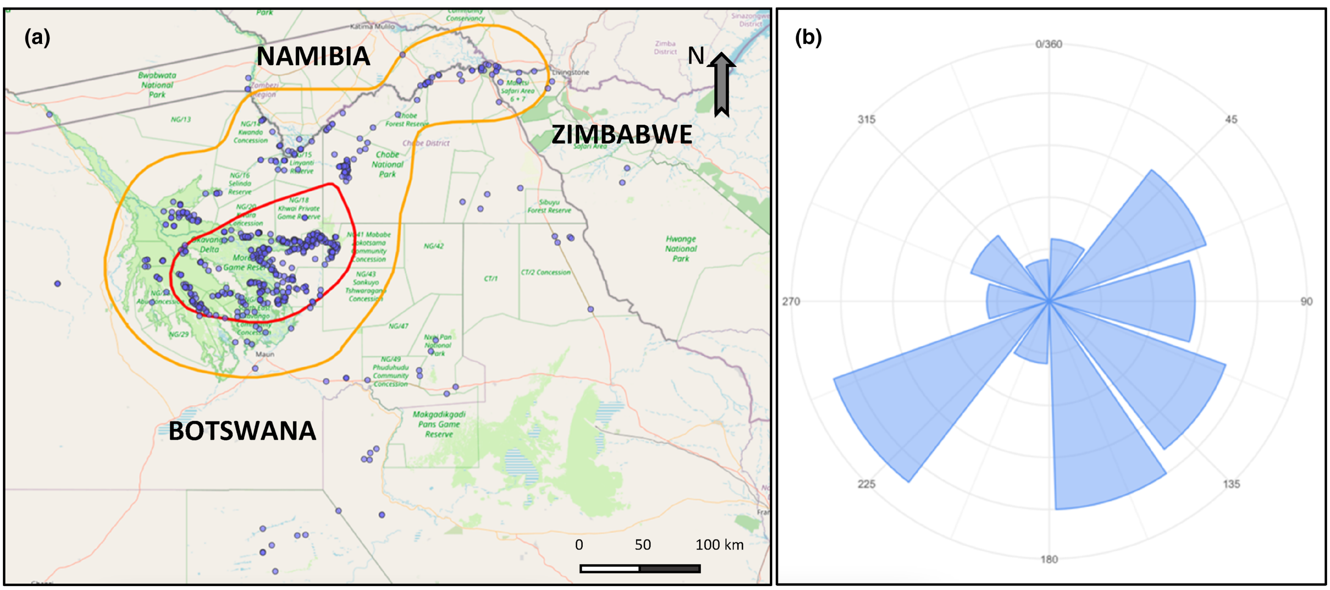

FIGURE 2 African wild dogs sighting distribution and locations across northern Botswana and adjacent countries (a) and directionality of movement as inferred by photographic information collected as sightings (b). In (a), the blue dots represent single sightings, the red inner polygon represents an area of roughly 8000 km^2 projected to containing half the sightings. The majority of the sightings are concentrated at the south-eastern end of the perennial waters of the Okavango Delta (highlighted in green). The outer orange polygon represents an area of 56,000 km^2 from which 90% of the sightings are generated. Underlaying map: OpenStreetMap. In (b), only individual dogs whose displacement was >25 km have been considered. Numbers correspond to the degrees with the north pole as reference. The height of each slice represents counts.

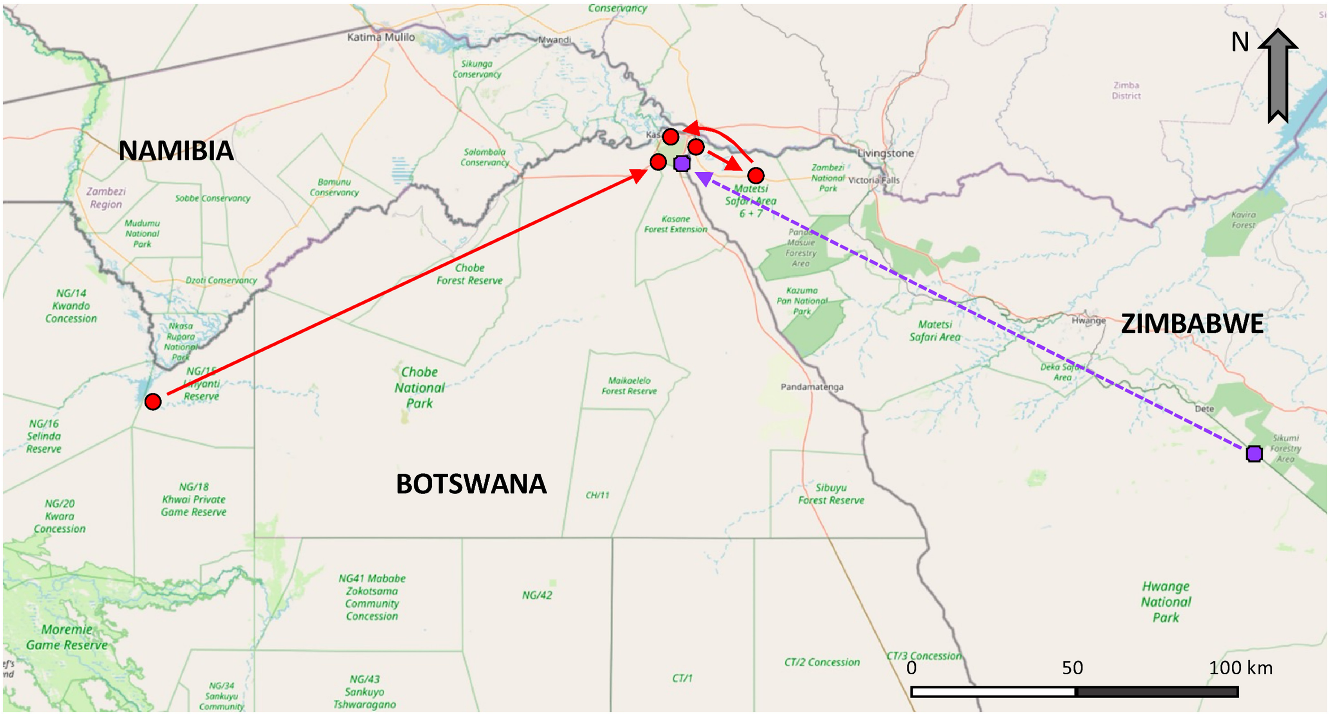

FIGURE 3 Examples of two long-distance, transboundary dispersal events documented by means of photographic evidence archived by independent research institutions and tourists. Curve lines do not represent actual trajectories but serve the purpose of simplify the graphic presentation. See Case 1 (purple octagons and dashed line) and Case 2 (red dots and solid lines) in the main text for further information.

concentrated within a core area of just >12,240 km^2 (50% isopleth). This core area, roughly 160 km along and 90 km across, was centred around the eastern side of Botswana's Moremi Game Reserve and adjacent Wildlife Management Areas where photographic tourism activities are concentrated (Figure 2). Movements of individuals from the core area mainly occurred towards a northeast to southwest range (Figure 2).

3.1 | Cases supporting long-distance transboundary movements and between-organisation information transfer

3.1.1 | Case 1

Pictures of African wild dogs taken by a tourist on 2018-10-20 at coordinates 25.23423°/−17.87376° (lon /lat) while on a trip in Botswana were sent to and archived by BPC as 'individuals of unknown origin'. An individual African wild dog known to the Zimbabwe-based PDC and part of their study population was defined as 'missing' in 2013, and its last record within the Zimbabwe study population was 2013-06-08 at coordinates 27.01840°/−18.75047° (lon/lat) (Figure 3). In July 2022, a match between these two independently archived instances, was found by PDC staff while *validating* candidate individuals offered as *matches* by the software. These two independent sightings were >5 years and 200 km apart, across international borders and owned and archived by two independent research organisations.

3.1.2 | Case 2

Pictures of African wild dogs taken by an independent researcher on 2017-09-27 at coordinates 23.56028°/−18.59343° (lon /lat) in Botswana were uploaded and archived as privately owned. During the *validation* process of target individuals within the pool of BPC-managed pictures, the individual photographed on 2017-09-27 (and not belonging to the BPC pool) was offered as a potential *match*. The same individual was seen and reported on five additional occasions, three of which were in Zimbabwe, by tourists who had sent their pictures to BPC. Dates and locations were as follow (1) 2017-09-27 at 23.56028°/−18.59343° (Botswana; not BPC pool); (2) 2018-10-20 at 25.234229°/−17.873759° (Botswana; BPC pool); (3) 2019-05-25 at 25.2724°/−17.82828° (Zimbabwe; BPC pool); (4) 2019-08-07 at 25.2724°/−17.82828° (Zimbabwe; BPC pool); (5) 2019-11-10 at 25.45199°/−17.91904° (Zimbabwe; BPC pool); (6) 2020-01-29 at 25.18887°/−17.79475° (Botswana; BPC pool) (Figure 3). Maximum straight-line distance covered by this individual was >200 km and cumulative distance >250 km, sightings were across international borders, and the same individual potentially recorded as part of several study populations.

4 | DISCUSSION

Our results showcase the potential and flexibility of the African Carnivore Wildbook (ACW), an open-source platform supported by artificial intelligence-based detection and individual identification algorithms (Crall et al., 2013; Parham et al., 2018) developed to speed and facilitate recognition of single individuals of African carnivore species collected across trans-boundary landscapes, organisations and institutions. The spatial extent of the data collected, and the vast number of pictures processed highlight the necessity of having an online and easily accessible GUI-based platform where users can conveniently upload their photographs and relative metadata that helps and enhances collecting, curating, managing and sharing of information from different sources among different parties.

Despite having run only a subset of the African wild dog pictures uploaded into ACW through *detection* and *matching*, information at the relevant spatial and temporal scale on dispersal and re-sighting of individuals presumed to be dead was obtained. A noticeable (10.8% of the total identified individuals) number of potential dispersal events or extra-territorial exploratory forays have been detected. The above-mentioned distance of 25 km between re-sightings, suggests that >10% of the individuals may have dispersed/be dispersing (natal dispersal or secondary dispersal) outside their former pack's home range. Indeed, 25 km roughly corresponds to the diameter of a hypothetical circular mean home range, calculated across different study areas, of 513 km^2 (Pomilia et al., 2015). In this study, we recorded four cases of long-distance movements >150 km, which is consistent with information obtained through GPS/Satellite radio collars for our study area (Cozzi et al., 2020; Sandoval-Seres et al., 2022). The spatial distribution of the sightings, despite being scattered across northern Botswana, were concentrated on a relatively small area in and around Moremi Game Reserve, which may have hindered detection of additional and longer dispersal events. Similarly, the concentration of the sightings at the southern end of the perennial swamps of the Okavango Delta (cfr. Figure 2) may be responsible for the observed directionality of displacement towards a northeast to southwest range, that is away from the Delta flooded areas. Avoidance of deep water is consistent with the knowledge that the permanently flooded regions of the Okavango Delta represent an obstacle to wild dogs (Cozzi et al., 2013; Hofmann et al., 2021, 2023). The relative spatial clustering of the sightings may thus have partly influenced these results, highlighting the need for increasing sampling effort through on-site information campaigns in under-sampled regions or via a larger-scale citizen science website. Researchers may be able to partly overcome such biases by intensifying data collection (e.g. through camera trapping) in areas little frequented by tourists or citizen scientists. A more comprehensive collection of photographic information and related metadata throughout the entire landscape will be central to allowing more precise inferences about patterns of long-distance movements and dispersal. In any case, such data are inherently skewed due to uneven observation efforts across the landscape, particularly as across landscapes with varying tourist accessibility. Nonetheless, the data obtained from the ACW can be combined with occupancy and abundance estimation methods, which account for variability in detection probabilities (e.g. Van der Weyde et al., 2021) partly overcoming such biases.

The use of pictures from tourists uploaded to the ACW also allows accurate spatial and demographic inferences at the local scale. For instance, the average relocation distance of roughly 10 km revealed in this study is in line with displacements of resident packs across temporal scales of variable duration (Pomilia et al., 2015). This realisation suggests that coarse movements and the spatial extent of pack territories can be estimated for different habitats across the KAZA/TFCA ecosystem, given sufficient sightings. However, the ACW has some inherent uncertainties with regard to pack size estimation and composition. Results here indicating an average number of 4 individuals per sighting where pack size averages 9–10 individuals (McNutt & Silk, 2008) suggest that several sightings per pack may be required to obtain a full pack composition. However, dispersing coalitions, which inevitably form part of the data set, are composed of an average of three to four individuals (Behr et al., 2020; Cozzi et al., 2020), and it is not uncommon for all individuals in smaller groups to be photographed in a single sighting. In addition, the current inability to automatically assign a left and right side to the same individual brings with it the risk of artificially inflating the number of individuals, as was likely the case of the 31 individuals identified in one sighting. Information about individual social relationships and group membership deriving from participating focal researchers may be used to improve matching of pack members as well as pairing of left and right sides of the same individuals.

The re-sighting of individuals over periods of up to 4 years (i.e. for almost the entire duration of the study) highlights the merit of the ACW platform in allowing individuals to be tracked throughout their lives and across geographical and political boundaries. Recently, individual-based statistical approaches have been developed to assign a fate (i.e. dispersed or dead) to individuals that disappear under unexplained circumstances (i.e. missing individuals) (Barthold et al., 2016; Behr et al., 2023). By confirming re-sighting of missing individuals whose fate was assigned as 'dispersed' (as opposed to 'unknown' or 'dead'), the ACW can be readily used as a platform to empirically validate such modelling approaches.

A key feature of ACW is that registered organisations or institutions retain full ownership and control over their photographic material and the metadata linked to it. This allows data owners to use outputs from the ACW for their local needs (e.g. at the scale of a single organisation's main study area) but also to *match* across organisations, without the risk of loss of data ownership or data leak. We believe that this feature is the basis for facilitating collaboration. The two cases reported in the Section 3 demonstrate how individual African wild dogs can move and enter populations monitored by independent organisations, and how organisations can collaborate to share such information. Without an online platform such as ACW, this connectivity is unlikely to be documented.

Due to the number of pictures, it has become evident that matching of individual pictures would only be achieved by means of technological support. It was beyond the scope of this manuscript to compare ACW speed and accuracy to other AI-based algorithms or human observers, for HotSpotter (the identification backbone of

ACW) has already been shown to outperform other algorithms (de Lorm et al., 2023). Regardless of the image-matching algorithm of choice, however, only an open-source and platform will offer the possibility to reach a critical number of users without limitations imposed by, for example computer skills or coding scripts that may not be made accessible to others.

Due to the ability to successfully match pictures among data sets of independent organisations, to track individuals across political boundaries, to record noteworthy dispersal distances, to deliver information on survival, the ACW is a promising tool to tackle some key ecological questions. These include, for example, investigation of dispersal distance, duration, and landscape permeability; assessment of source and sink populations through inference of patterns of immigration and emigration; research into philopatry and its covariates; validation through empirical data of mathematical models aimed at assigning a fate to missing individuals; exploration and proof of modelled dispersal connectivity; evaluation of dispersal directionality with implications for gene flow and dynamics of disease transmission; support of patterns of occupancy and abundance inferred with more traditional methods such as camera trapping or field observations. Furthermore, the direct involvement of tourists through their photographic material enhances and facilitates outreach and management endeavours crucial for the successful conservation of threatened and endangered large carnivore species.

In conclusion, we believe that due to its ability to process and match individuals across tens of thousands of pictures and its structure that secures data ownership while allowing for transfer of information, the easily accessible online ACW could become the platform of choice for the automated identification of African carnivores locally but also across international boundaries and independent research organisations and entities. We would encourage research teams and ecotourism companies alike to enable their staff and tourists to share information about the ACW to contribute to a growing collective body of knowledge. Adaptations of the same underlying identification algorithm and similar data ownership approach is already implemented for other African carnivore species and could also be expanded and applied to other ecosystems and species.

AUTHOR CONTRIBUTIONS

Gabriele Cozzi, Maureen Reilly, Paul Kalil and John Weldon McNutt conceived this study. Gabriele Cozzi, Maureen Reilly, Paul Kalil and Jason Holmberg developed the African Carnivores Wildbook tool. Gabriele Cozzi, Daniela Abegg and David D. Hofmann analysed the data. Gabriele Cozzi wrote the first draft of the manuscript. All authors helped with data collection, and they commented on and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

All the authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in African Carnivores Wildbook at https://www.africancarnivorewildbook.org.

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SUPPORTING INFORMATION

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

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