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Advancing animal behaviour research using drone technology

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Unmanned aerial vehicles or drones have revolutionized wildlife monitoring, and they are increasingly being used to study animal behaviour. In this review, examples of how data captured by drones (primarily images and video) enable the study of animal behaviour in less accessible environments, as well as rare or elusive behaviours, are provided. We believe that the potential application of drone imagery to advance wildlife monitoring creates unique opportunities for animal behaviour research and conservation. Rapid advances in image-tracking technologies and the use of artificial intelligence to identify the position, behaviour and local environment of many individuals simultaneously allow for the automated collection and processing of large data sets. Moreover, drones allow researchers not only to observe but also to manipulate and alter animal behaviour, creating a biohybrid system (i.e. a system involving an interaction between biological and engineered components, as discussed in this special issue), enabling the systematic study of specific behaviours, such as responses to simulated predation risk, or managing animal groups in agricultural settings and human–wildlife conflict scenarios. However, effective drone usage is a difficult task, requiring consideration of many aspects. We highlight the importance of user proficiency in drone piloting and the challenges of processing and analysing the vast amount of data they create. In addition, we provide some insights into the importance of carefully considering the study species and context for animal behaviour research. Various methods of dealing with landscape and interindividual heterogeneity in studies across different species are also suggested. Finally, some ethical considerations and potential unintended consequences of drone usage are discussed.

Over the last decade, unmanned aerial vehicles (UAVs) or 'drones' have become commonly used for wildlife and natural habitat monitoring (Mo & Bonatakis, 2022), including estimation of animal population sizes and habitat mapping (Chabot & Bird, 2015; Christie et al., 2016; Jiménez López & Mulero-Pázmány, 2019; Mo & Bonatakis, 2022). Drones can cover greater distances at higher speeds than on-foot surveys and can travel with greater flexibility, less cost and lower risk for researchers compared with manned aircraft (Christie et al., 2016; Jiménez López & Mulero-Pázmány, 2019; Linchant et al., 2015; Pierry et al., 2023). In addition, the use of drones can minimize disturbance caused to study species compared with ground surveys (Corregidor-Castro et al., 2022; Krause et al., 2021) or observations made from boats and manned aircraft, thanks to their small size and diminished noise output (Christie et al., 2016; Linchant et al., 2015; Martin et al., 2022; Puszka et al., 2021; Sobreira et al., 2024).

Recently, drones have been used to advance the study of animal behaviour. In addition to standard images, drones can carry thermal cameras to study elusive and nocturnal species (Gooday et al., 2018; McKellar et al., 2021; Zhang et al., 2020) and can capture audio data when fitted with microphones (for cetaceans, Frouin-Mouy et al., 2020; for bats, Kloepper & Kinniry, 2018; for birds, Michez et al., 2021). Drones can also be used to directly influence and manipulate animal behaviour (King et al., 2023) and can be fitted with speakers to provide specific cues to animals (Yaxley et al., 2021). Recent advances in artificial intelligence (AI) and computer vision techniques have allowed automated analysis of images collected by drones (Kholiavchenko et al., 2024; Koger et al., 2023; Ozogány et al., 2023), enabling researchers to individually identify animals and easily quantify their interactions

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with their social and physical environments (Kholiavchenko et al., 2024; Price et al., 2023).

Using drones to study behaviour is not trivial; it requires an appropriate take-off and landing area, and their use is affected by environmental conditions, such as rain and wind (Duffy et al., 2018). Drones can also cause disturbance to focal animals and to the wider ecosystem (see the 'Ethics, law and safety' section). Moreover, drones can provide data that are not attainable via direct survey or observation, often enabling closer proximity to the study organisms without disrupting their natural behaviours (Pollock et al., 2022; Robbins et al., 2019; Torres et al., 2018). Drones also provide greater flexibility in the images they can capture compared with camera traps, which have a limited field of view and position-specific constraints (Ballard et al., 2014; Findlay et al., 2017; Glen et al., 2013; Palencia et al., 2022). In fact, analyses of drone images provide high-resolution individual-based movement and behavioural data, such as those provided by animal-attached tags or 'bio-loggers' (Brown et al., 2013; Cagnacci et al., 2010; Fehlmann & King, 2016; He et al., 2023; Williams et al., 2020; Wilmers et al., 2015).

Although bio-loggers and drones are both suitable for studying large organisms, drones can be used to observe many individuals simultaneously. Tagging multiple individuals to acquire data on groups or populations is often impractical with bio-logging techniques; although a growing number of studies have achieved this (Farine et al., 2017; Haddadi et al., 2011; Harel et al., 2021; King et al., 2012; Papageorgiou & Farine, 2020). Bio-logger data can span months or even years (Fehlmann & King, 2016; Kays et al., 2015), whereas drones are restricted to observations over a few hours at most (Iwamoto et al., 2022). Nonetheless, the two approaches can be combined, with drones programmed to locate mobile tags (Chen et al., 2024) and autonomously track them (Bayram et al., 2017; Nguyen et al., 2019; Shafer et al., 2019) to collect data at a finer scale, at individual and group levels.

In this review, we explore how animal behaviour research can be advanced using drone technology (Fig. 1). First, we highlight the use of drones for studying animal behaviour in less accessible environments and for capturing elusive behaviours. Next, we discuss the advantages that drones provide for studying the interplay between the environment (social and physical) and individual behaviour and the ways in which behaviour and biodiversity monitoring can be integrated to proactively address conservation and management issues. Then, we assess the potential application of drone technologies not only to observe, but also to react and interact with animals in controlled experiments to advance animal behaviour research (Papadopoulou et al., in press) and in herding scenarios where drones can be used to keep animals away from specific areas (e.g. crop fields and airports; King et al., 2023). Finally, we identify the challenges, as well as ethical and unintended implications, of using drones to study animal behaviour.

OBSERVING ANIMAL BEHAVIOUR USING DRONES

Drones enable animal behaviour research in environments that are difficult to access and often provide insights into elusive or rarely observed behaviours (Table 1). Flying drones over water, researchers can obtain a unique bird's-eye view, which is ideal for

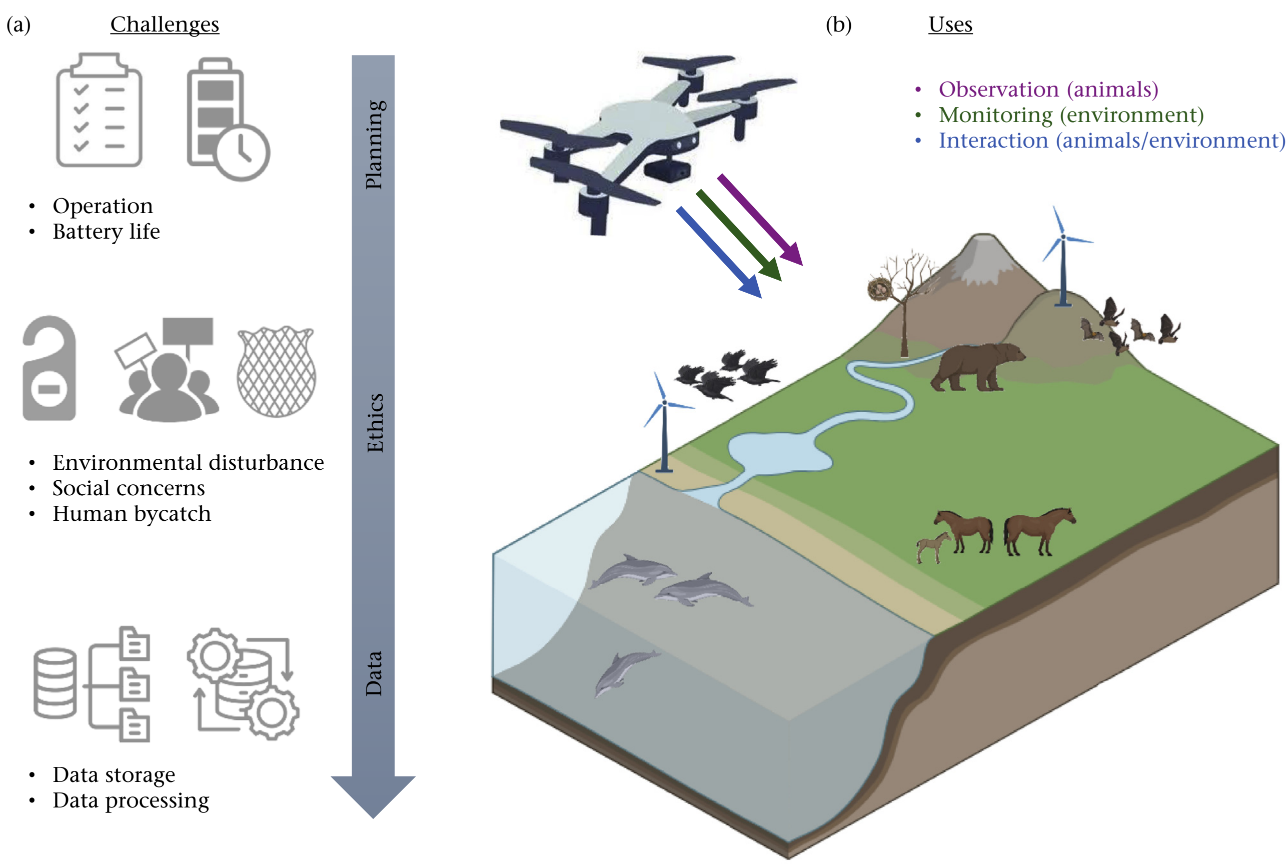

Figure 1. Advancing wild animal behaviour research through drone technology. (a) Challenges (regarding planning, ethics and data) faced before, during and after data collection using drones. (b) Use of drones in animal behaviour research to observe animal behaviour, for example social dynamics of herding ungulates (Mendonça et al., 2023; Ozogány et al., 2023), surface behaviour of marine animals (Torres et al., 2018) or for habitat monitoring and classification (Assmann et al., 2020). Drones can also be used to interact with animals or the environment by altering behaviours to reduce negative human–wildlife interactions, such as herding (Hahn et al., 2017), or conducting behavioural experiments, such as antipredator responses (Zhou et al., 2023). All images are the authors', or subject to royalty free creative commons licences.

Table 1
Examples of animal behaviour studies using drones, with details on data collection method and local environment

Topic	Studied animals	Drone	Flight altitude (m)*	Environment	Source
Acoustic behaviour	Grey whales	DJI Phantom 4 advanced; Plus Swellpro SplashDrone 3+ (+ hydrophone)	30	Lagoon	Frouin-Mouy et al. (2020)
	Mexican free-tailed bat	DJI Spreading wings S900 (+ microphone)	5–50 (from cave entry)	Cave	Kloepper and Kinniry (2018)
	Birds Bats	DJI Phantom 3 Pro (+ microphone)	20–40–60 20	Meadow	Michez et al. (2021)
Antipredator response	Common eiders	DJI Phantom 3 Pro; DJI Phantom 4 Pro	30–55	Open tundra	Simone et al. (2023)
Behavioural development	Right whales	DJI Phantom 3 Pro; DJI Inspire 1 Pro	20–100	Coastal waters	Nielsen et al. (2019)
Breeding distribution	Loggerhead sea turtles	DJI Phantom 3 Pro	60	Coastal waters	Dickson et al. (2022)
Breeding status	Chaco eagles	DJI Phantom 3	5–10 (from nest)	Plain	Gallego and Sarasola (2021)
	Ospreys	Draganflyer X-4	3 (from nest)	Riparian valley	Junda et al. (2015)
	Ferruginous and Red-tailed Hawks		3–6 (from nest)	Prairie	
	Bald eagles		<15 (from nest)	Boreal forest	
	Ravens	DJI Mavic Air	2–4 (from nest)	Pine forest	Zawadzki and Zawadzka (2024)
Collective movement	Exmoor ponies	DJI Mavic 2 Pro	80	Meadow	Kavwele et al. (2024)
	Long-finned pilot whales	DJI inspire 1 V2	25	Coastal waters	Zwamborn et al. (2023)
Foraging behaviour	Stingrays	DJI Phantom 3 standard	3–5	Sandflat	Crook et al. (2022)
	Polar bears	DJI Phantom 3 Pro; DJI Phantom 4 Pro	30–55	Open tundra	Jagielski et al. (2021)
	Terns	DJI Phantom 3	100	Tidal channel	Lieber et al. (2021)
Interspecific interaction	Killer whales Harbour seals	DJI Mavic 3	?	Coastal waters	Hague et al. (2022)
Movement behaviour	White sharks	DJI Phantom 4	20–25	Coastal waters	Colefax et al. (2020)
	Grevy's zebras Gelada monkeys	DJI Phantom 4 Pro	80 70	Savanna	Koger et al. (2023)
Nocturnal behaviour	Hainan gibbons	DJI M600Pro (+ thermal camera)	380 50 (from canopy)	Rainforest	Zhang et al. (2020)
Reproductive behaviour	Blackbucks	DJI Air 2S	80–110	Grassland	Naik et al. (2024)
	Dusky dolphins	DJI Phantom 4	10–50	Coastal waters	Orbach et al. (2020)
Social behaviour	Feral horses	DJI Mavic Pro	?	Mountains	Mendonça et al. (2023)
	Przewalski's horses	DJI Phantom 4	10–30 100–300	Steppe	Ozogány et al. (2023)
Spatial distribution	Waterbirds	DJI Phantom 4 Pro	75–80	Intertidal flat	Castenschiold et al. (2022)
	Seabirds	DJI Mavic Pro; DJI Phantom 3 Advanced	61–74	Tidal channel	Costagliola-Ray et al. (2022)
Surface behaviour	Bottlenose dolphins	DJI Phantom 4 Xtreme Vision360 HexH2O TM	25–40	Coastal waters	Fettermann et al. (2022)
	Humpback whales	Xtreme Vision360 HexH2O TM	30	Coastal waters	Fiori et al. (2020)
	Blue whales	DJI Phantom 3 Pro; DJI Phantom 4 Advanced	29–38	Coastal waters	Torres et al. (2018)
Swimming kinematics	Manta rays	DJI Mavic Pro 2	<15	Coastal waters	Fong et al. (2022)

* Flight altitude measured from ground level, unless stated otherwise.

observing animal behaviour on and below the surface, even up to 25 m deep (Torres et al., 2018). This technique has enabled investigations into near-shore movement patterns of white sharks, *Carcharodon carcharias* (Colefax et al., 2020), kinematics of manta ray, *Mobula cf. birostris*, swimming (Fong et al., 2022) and activity budgets for numerous cetacean species (Fettermann et al., 2022; Fiori et al., 2020). Drone use has also enabled the study of the rarely observed nursing behaviour of Southern right whales, *Eubalaena australis*, revealing the relationship between the energetic costs, for calves and mothers, and calf size, which is calculated by converting pixels in the images to metres (Nielsen et al., 2019). Similarly, pixel coordinates can be converted to geo-referenced coordinates to track animal movements across 2D (pixel space) or 3D landscapes (Koger et al., 2023).

Above land, drones allow the study of animal interactions where direct observation would pose direct risks to researchers and animals (Clark et al., 2012). For example, the foraging behaviour of polar bear, *Ursus maritimus*, has been observed by using drones (Jagielski et al., 2021), thereby avoiding potential bear attacks towards humans (Clark et al., 2012). Drone footage is also ideal to spot rare behaviours. When recording bear behaviour using drones, researchers observed conspecific nest attendance by the common eider ducks, *Somateria mollissima*, in response to polar bear attacks (Simone et al., 2023). Bird nesting behaviours can be observed with little disturbance to the birds and reduced fieldwork effort (Gallego & Sarasola, 2021), allowing the monitoring of birds' breeding success ranging from ravens, *Corvus corax* (Zawadzki & Zawadzka, 2024), to raptors, *Buteo jamaicensis*, *Buteo regalis, Haliaeetus leucocephalus* and *Pandion haliaetus* (Junda et al., 2015).

Although specific animal behaviours may be common, such as resting or sleeping, the presence of observers can disrupt or halt the behaviour completely, even in habituated individuals (McDougall, 2012). To avoid disturbances, drones equipped with thermal cameras have allowed researchers to study sleeping behaviour in critically endangered Hainan gibbons, *Nomascus hainanus*, in their natural habitat (Zhang et al., 2020) and to monitor night-time behaviour of European brown hares, *Lepus europaeus*, providing better data compared with the commonly used line transects spotlight counts (Povlsen et al., 2023). Microphones are also a valuable addition to drones, for instance employed to investigate the vocalization of Mexican free-tailed bats, *Tadarida brasiliensis*, as they enter their roosts (Kloepper & Kinniry, 2018). In both cases, the addition of specific data collection devices (thermal cameras or microphones) has yielded unique data with minimal disturbance. Moreover, drones can be combined to capture complementary data streams, such as integrating video with audio recording (Michez et al., 2021). For example, behaviours and vocalizations of grey whales, *Eschrichtius robustus*, have been recorded by deploying two drones simultaneously, one drone above the animal group collecting image data and the other drone nearby with a hydrophone collecting audio data (Frouin-Mouy et al., 2020).

PROVIDING ENVIRONMENTAL CONTEXT

Drones are most valuable because they can provide environmental context to the behaviours observed (Table 1), enabling researchers to study the occurrence and temporal dynamics of interactions between animals and their surroundings (Biro et al., 2016; Cantor et al., 2023; King et al., 2018). Drones can make observations from different heights; thus, they can be used to observe entire animal groups or populations (Ayres et al., 2021; Castenschiold et al., 2022; Dickson et al., 2022). Therefore, drones are useful for investigating group-level behaviour and movements (Fig. 2), which can be impractical or costly when using direct observations, camera traps or bio-loggers (Costa-Pereira et al., 2022; Hughey et al., 2018).

Although drones provide 'snapshots' of collective behaviour, recent work suggests these short periods of data provide insights into group and population dynamics. At the sea surface, drone footage of long-finned pilot whales, *Globicephala melas*, surfacing and diving has allowed tracking of collective movements and leadership (Zwamborn et al., 2023). In addition, drone flights with a maximum time span of only 20 min have revealed differences in mating strategies for 25 different groups of dusky dolphins, *Lagenorhynchus obscurus* (Orbach et al., 2020). On land, drone imagery of feral horses, *Equus ferus caballus*, has enabled the construction and analysis of their antagonistic and affiliative networks (Mendonça et al., 2023). In Przewalski's horses, *E. ferus przewalskii*, a few minutes of fine-scale movement data from drone-based image analyses has allowed researchers not only to reconstruct past group dynamics of the horses, but also to predict future ones (Ozogány et al., 2023). If these snapshots are inadequate, then drone footage can be combined with other methods. For example, intermittently filming the behaviour of GPS-tagged Exmoor ponies, *E. ferus caballus*, has allowed the characterization and analysis of social interactions, which would not have been possible from one or a few GPS trajectories (Kavwele et al., 2024).

With precise data on spatiotemporal distribution patterns of individuals (Castenschiold et al., 2022; Costagliola-Ray et al., 2022; Larsen et al., 2022), animal space use can be linked to environmental variables at different scales. At an individual scale, drones have been used to investigate the relationship between water turbulence in tidal seas and foraging opportunities in different species of terns such as *Sterna hirundo*, *S. paradisaea* and *S. sandvicensis* (Lieber et al., 2021). High-quality drone images have allowed researchers to extract tern trajectories using machine learning techniques and quantify water surface velocity fields using particle image velocimetry methods (Lieber et al., 2021). At a population scale, drone images have been used to investigate the influence of wind on breeding aggregations of several sea turtles, *Caretta caretta* (Dickson et al., 2022), and research has even extended to species interactions and ecosystem-level effects. For example, drone data have revealed that mussel farms serve as refuges for harbour seals, *Phoca vitulina*, during killer whale, *Orcinus orca*, attacks (Hague et al., 2022), and drone images of two stingray species, *Himantura australis* and *Pastinachus ater*, have provided insights into their functional roles in the ecosystem (Crook et al., 2022). The different feeding strategies used by the sympatric stingray species had different, yet complementary, effects that enhanced ecosystem productivity, one resulting in ecosystem engineering impacts and the other promoting nutrient dispersal over a large area (Crook et al., 2022).

ANIMAL BEHAVIOUR AND BIODIVERSITY INTEGRATION

Behavioural changes are often the initial responses observed in organisms subject to environmental shifts (Rahman & Candolin, 2022; Wilson et al., 2020). Thus, the use of drones to monitor animal behaviour and the environment provides a unique opportunity to integrate behaviour and biodiversity research. For example, many ungulate species have seasonal migrations in search of food and suitable breeding areas (Kauffman et al., 2021). Shifts in

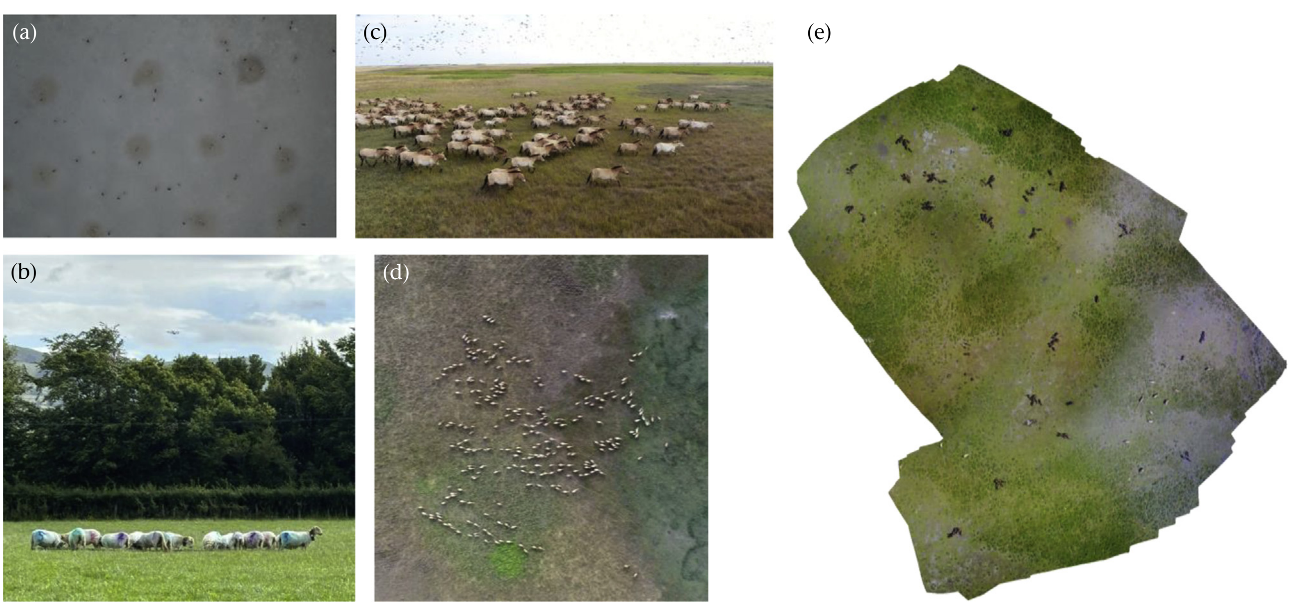

Figure 2. Use of drones for animal behaviour research. (a) Field study of blackbuck mating systems in Tal Chaapar Sanctuary, Rajasthan, India, filmed using DJI Air 2S (Naik et al., 2024). Behavioural interactions at leks recorded using UAVs are quantified automatically by tracking the movement of animals using computer vision algorithms. Photo credit: Hemal Naik, Akanksha Rathore, Vivek Hari Sridhar, Project MELA (Mating Ecology of Lekking Antelopes). (b) Study of sheep behaviour at Bangor University's Henfaes Research Centre, Wales, U.K. A DJI Mini 4 Pro can be seen just above the tree line filming above the sheep flock. Photo credit: Lucia Pedrazzi. (c, d) Field study of Przewalski's horses at Pentezug Reserve, Hortobágy National Park, Hungary (Ozogány et al., 2023), filmed using a DJI Phantom 4 drone at 15 and at 150 m above ground level. The drone flying higher provided a top-view image for tracking individuals to obtain their movements in an earth-fixed coordinate system. Photo credit: Katalin Ozogány. (e) Study of feral horses in Serra D'Arga, Portugal (Maeda et al., 2021). This is an orthomosaic image created with Agisoft Photoscan Professional, using images taken by a DJI Mavic Pro. Photo credit: Tamao Maeda.

vegetation distribution caused by climate change can alter animal foraging patterns, leading to changes in species distribution (Brivio et al., 2019; Severson et al., 2021) and inter- and intraspecies interactions, such as predator–prey dynamics (Carroll et al., 2024; Hone et al., 2011). Therefore, behaviour serves as a mediator of ecological responses across high organizational levels, making it indispensable for effective biodiversity monitoring (Berger-Tal et al., 2011).

We propose that drone images (Fig. 3a) combined with AI and computer vision algorithms can be used to link behaviour and biodiversity research. AI models used to identify animals in the wild from UAV images now exist (Corcoran et al., 2021). Moreover, large-scale data sets (Naik et al., 2024) are being created to detect and track animals in different habitats with various imaging modalities. The data sets can also be used to standardize method development and data collection protocols, for example species-specific guidelines on flying altitude based on habitats, flight modality and behaviour. Frameworks to automatically quantify animal behaviour using movement and postures from images in controlled settings have also been developed (Kellenberger et al., 2020; Price et al., 2023). There are even attempts to link behaviour (state and social interactions) and monitoring (identification and counting) in the wild using one (Koger et al., 2023) or more UAVs (Naik et al., 2024). Using these types of methods, animal positions and behaviour can be tracked (Fig. 3b) to create activity budgets and spatial and social associations (Fig. 3c). Automated frameworks grounded on drone data analysis can further be used for biodiversity monitoring through species identification and habitat classification (Fig. 3d), providing information on species distribution and diversity (Fig. 3e). Combining these data and analyses (Fig. 3f) can improve our understanding of ecosystem stability across diverse spatial and temporal scales (Assmann et al., 2020; Siewert and Olofsson, 2020) and the role of species within their ecosystems (Crook et al., 2022). This understanding is critical for effective conservation efforts and the long-term health of the environment (Lindenmayer et al., 2007). This approach also enables researchers to monitor animal behaviour in response to environmental shifts, which can serve as an early warning system for potential ecosystem disruptions (Wilson et al., 2020). Collectively, researchers can use this information to proactively address conservation and management issues, thereby preventing or mitigating adverse effects on biodiversity (Rahman & Candolin, 2022).

MANIPULATING AND MANAGING ANIMAL BEHAVIOUR

As remotely controlled objects that can safely interact with animals, drones show great potential for use in field experiments. Drones can be used not only to observe, but also to alter the

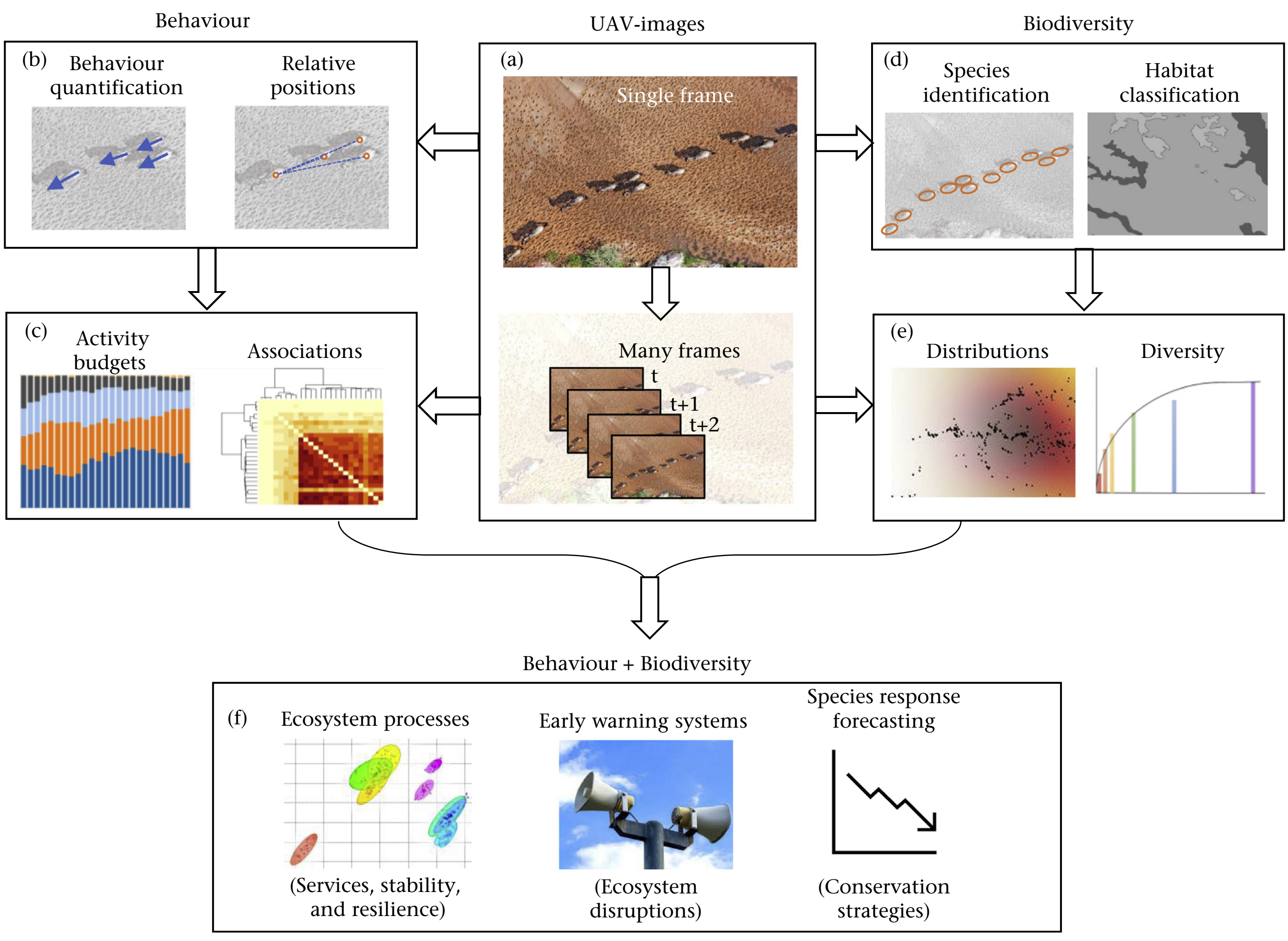

Figure 3. Integrating drone use into behaviour and biodiversity research. (a) Drone images can be used to obtain information on (b) animal behaviour and relative positions in any frame, which can be integrated to produce (c) activity budgets and association patterns and (d) identify species and classify habitats, allowing for (e) estimated distributions and diversity over spatial scales. Combining data is critical to (f) understanding of ecosystem processes, providing early warning systems, and forecast species responses to change. All images are the authors', or subject to royalty free creative commons licences.

behaviour of individual animals or groups. Thus, researchers facilitate an active interaction between the drone and the animals, thereby creating a biohybrid system, which is the topic of this special issue ((Papadopoulou et al., in press)). This biohybrid approach can be helpful in studying the development, mechanism and function of animal behaviour.

Drones can mimic an aerial predator without posing a real threat, thereby prompting an antipredator behavioural response. For example, Zhou et al. (2023) used drones to simulate predation risk in a population of plateau pikas, *Ochotona curzoniae*. They found that such species showed antipredator behaviour towards the approaching drone, which was absent when the animals could only hear but not see the drone, indicating that the visual stimulus likely elicited the antipredator response (Zhou et al., 2023). Drones have also been presented to species that experience no aerial predators in their natural habitat to study the evolutionary origin of these antipredator responses. West African green monkeys, *Chlorocebus sabaeus*, which lack natural aerial predators, have developed alarm calls towards the drones like those used by closely related East African vervet monkeys, *Chlorocebus pygerythrus*, which regularly encounter birds of prey (Wegdell et al., 2019). This information revealed an evolutionary component to predator avoidance behaviour that seems to be preserved across closely related species (Wegdell et al., 2019). Compared with pikas, the green monkeys reacted to the drone sound alone after their initial encounters (Wegdell et al., 2019). In social groups, the approach of drones can be used to study collective escapes, and the response of blackbuck herds, *Antilope cervicara*, to drones provided video imagery from which researchers extracted a host of data on changes in individual positions, speed, conspecific attraction, alignment, cohesion and polarization over time (Rathore et al., 2023).

The fundamental animal behaviour research into antipredator responses using drones suggests the use of drones as deterrents, eliciting escape responses to move animals away from dangerous or sensitive areas. For example, drone approaches provoked flight responses in white rhinos, *Ceratotherium simum simum*, simulating dispersal from a poaching area (Penny et al., 2019). Similarly, African savannah elephants, *Loxodonta africana*, have been effectively guided away from crop fields to a safe distance within a relatively short time (Hahn et al., 2017). Drones have also been used to deter blackbirds, *Icteridae*, from crop foraging, but this method does not work as well when birds are in larger fields and for larger flocks (Egan et al., 2023). Therefore, identifying the behavioural responses of animals to drones and investigating their potential habituation or sensitization effects are important (King et al., 2023).

Bio-inspired herding (i.e. herding of animal groups with an engineered system; King et al., 2023) has been applied by farmers to manoeuvre livestock (Yaxley et al., 2021). However, livestock can quickly adapt to drones. For example, cattle become habituated to drones after just 1 day (Anzai & Kumaishi, 2023). Although sheep respond (flee) when approached by a drone repeatedly, they show a marked decrease in their heart rate (Yaxley et al., 2021). Drones can be used not only as a ‘push’, but also as a ‘pull’ stimulus, providing novel opportunities for livestock and wildlife management. For example, a group of over 100 semiferal ponies, *Equus caballus*, were successfully lured into simulated traps, even in an area typically avoided by the animals (McDonnell & Torcivia, 2020). Remarkably, these ponies did not require prior conditioning because of their innate curiosity towards novel objects. In general, researchers can use positive conditioning (drone paired with food) to create an appetite for following drones (McDonnell & Torcivia, 2020).

Bio-inspired herding has also been successfully used to mitigate human–wildlife conflict that arises from collisions of flying animals with human-made structures or with aircraft (Metz et al., 2020) and wind turbines (Agudelo et al., 2021). For example, turkey vultures, *Cathartes aura*, avoid specific areas when researchers approach with a drone (Pfeiffer et al., 2021). Notably, a multirotor drone outperformed a fixed-wing drone because it could hover in the same area for longer periods, eliminating the need for wide turns when interacting with birds (Pfeiffer et al., 2021). Therefore, the type of drone used matters. Similarly, the mobility of drones was found to be important in preventing bat collisions with wind turbines (Werber et al., 2023). Using a modified drone equipped with continuous motion, sound and light emissions, researchers could avoid habituation to a specific stimulus, thereby preventing collisions among these cryptic, nocturnal species (Werber et al., 2023).

PRACTICALITIES AND CONSIDERATIONS

In this review, we have suggested multiple advantages of using drones, but their effective use can be hindered. Effective drone mission planning and execution is important for collecting relevant data sets with minimal disturbance to animals (Weston et al., 2020). The behaviour of some animals may be time sensitive, and data collection in protected areas may be limited. Therefore, a good data collection strategy with consideration of all closely linked parameters is necessary to achieve a successful outcome of the study. For example, the appearance of an animal is important for AI-enabled image or video-based studies. This factor is affected by the drone’s flying altitude and its motion, the size and position of the animal, the camera angle and its resolution and the frame rate of video recording. The AI algorithm selected for automated processing also defines constraints of the data collection strategy with regard to choosing suitable habitats, such as variations in light conditions, occlusions and background noise (Duffy et al., 2018).

Other practical limitations, including data storage and battery life, have also been identified. High-quality video data sets require storage space from several gigabytes to a few terabytes. Storing such a large volume of data requires additional planning to account time for storing data and conducting periodic backups, especially when operating in remote areas. Similarly, the battery life of drones is usually limited to under 60 min of continued operation, which hinders the feasibility of conducting long-distance flights for collecting continuous periods of data. Researchers may address this issue by using multiple batteries or drones, operating collaboratively as a swarm or relay system (Li et al., 2022). Users must consider logistics such as take-off or landing points and then define recording specifications and a stepwise plan to manage recordings. A well-thought-out recording strategy also includes timely documentation and checklists to reduce redundancy in data collection and avoid unwanted loss of data post recording. Other technical drawbacks include the dependence of flight stability on favourable weather conditions (i.e. without rain or wind), thereby restricting operational days and habitats suitable for drone deployment. In addition, the low payload capacity of drones restricts the types of devices (cameras, microphones and antennas) that can be integrated onto the platform. Therefore, selecting the appropriate drone model (size, weight, payload capacity and battery life) for specific research requirements can optimize performance in various ecological contexts.

Drones create extensive data sets, making their processing laborious and time consuming, especially if performed manually, as the most used data types are images or videos. Thus, automated feature extraction from images/videos using deep-learning algorithms, particularly convolutional neural networks, has been increasingly used for species identification, counting, tracking, behaviour recognition (Chen et al., 2023; Petso et al., 2021) and pose estimation (Graving et al., 2019; Nath et al., 2019; Pereira et al., 2022). Deep-learning techniques have also been successfully applied in precision livestock farming to detect, classify and localize different farm species (Yousefi et al., 2022). However, manual inspection and confirmation of the automated processed data remain necessary in most cases to ensure accuracy (Dujon et al., 2021). In addition, setting up a large-scale data processing software pipeline for wildlife monitoring is not a simple task. Most AI solutions are not developed with data sets including wild animals, as most publicly available data sets include humans and human-made objects for training machine learning algorithms. Therefore, pretrained models cannot be used directly with animal-derived data without extensive fine tuning. The creation of shared data banks housing images or videos of wildlife would avoid sacrificing time or data. At present, most computer vision and AI-based methods depend on transfer learning, which requires users to prepare a customized data set to adapt the model to work with their study species. Training models requires expensive computing hardware, a comprehensive understanding of preparing data sets and skillset to modify existing algorithms to work with customized data. The development of effective solutions can be motivated with strong collaborations between ecology and computer science departments within and across research institutions, creating interdisciplinary collaborations. Ecologists can produce novel data sets with wild animals, and computer scientists can develop fast and easy methods to extract important information from data. For example, an extensive data set of pigeons' poses automatically annotated in 2D and 3D (3D-POP: Naik et al., 2023) was used to create a framework to track 3D postures of up to 10 pigeons simultaneously (3D-MuPPET: Waldmann et al., 2024). Similarly, developing user-friendly open-source R packages can benefit the scientific community because R is a widespread programming language among biologists (Lai et al., 2023). For example, Machado and Cantor (2022) developed an R package (MAMMals) to extract metadata from different data types (photos, videos, locations and audios) and to sync them based on the individual and timing.

ETHICS, LAW AND SAFETY

Drones provide a unique observational tool and often reduce disturbance among study animals compared with other observation methods. However, minimizing disturbance is only achieved when researchers adhere to specific guidelines, which vary depending on the terrain, environment and geographical location (Weston et al., 2020). Moreover, responses to drones vary among species, although birds are usually more affected than mammals (Mulero-Pázmány et al., 2017). Therefore, reducing the detectability of the drone is important, from a visual and acoustic perspective. First, drones should be operated at an appropriate altitude, depending on the studied species and data quality needed, which can span from ca. 10 m for aquatic animals (Fong et al., 2022; Orbach et al., 2020) to approximately 60 m for terrestrial large mammals (Bennitt et al., 2019) and 80 m for birds (Castenschiold et al., 2022; Costagliola-Ray et al., 2022). Second, users should reduce the noise impact by opting for a more silent drone, such as an electrical one (Mulero-Pázmány et al., 2017), or by adjusting the flight altitude based on the species' hearing abilities and the way noise propagates within their environment (Duporge et al., 2021). In addition, take-offs and landings should be conducted at a distance from the animals, with an overhead flight pattern used to approach them, rather than a targeted trajectory (Christie et al., 2016; Mulero-Pázmány et al., 2017). For example, African ungulates exhibited avoidance behaviour when a drone flew within 100 m, approaching horizontally at an altitude of 10–30 m above ground level (Bennitt et al., 2019). As in any animal behaviour research, careful consideration should be given to ethical issues, and effort should be made to minimize adverse consequences (ASAB Ethical Committee/ABS Animal Care Committee, 2023). Institutional ethical approval should be sought prior to data collection. To date, although behavioural responses to drones have been studied in various species (Christie et al., 2016; Mulero-Pázmány et al., 2017; Weston et al., 2020), research into physiological stress responses are limited (Ditmer et al., 2015; Yaxley et al., 2021) and are often not feasible because of limited access or proximity to the study animals (and hence the use of drones in the first place, e.g. remote areas). Nonetheless, it should be good practice to provide full descriptions of the (1) animals' behavioural responses to drones, with a comparison to a control condition when possible (i.e. absence of the drone), as well as (2) drone (size, mass, etc.) and (3) flight specifications (height, speed, flight duration, flight schedule, etc.), in any published research. Although such information is species and context dependant, it could provide valuable insights for future studies.

Various ethical and safety concerns are related to the potential effects of drone use on humans (Sandbrook, 2015). These effects could be intentional, for example using drones to steer wildlife away from hunters might impact their livelihoods, making it important to consider in advance whether this is a legitimate intervention. In other cases, impacts might be unintentional, for example a drone taking video of wildlife might inadvertently capture data on humans. Such data could include direct images of people or human activities and land use (such as farms, homes or fishing nets). This unintended data collection has been described as ‘human bycatch’, by analogy to the accidental harvesting of nontarget species in fisheries, and it occurs frequently with the use of camera traps (Sandbrook et al., 2018). Evidence shows that the use of drones in a conservation context can be harmful to residents and their relationships with park authorities, unless local residents are the ones using drones for conservation (Millner et al., 2024). Similar issues could arise from the use of drones in animal behaviour research.

In mitigating the above-mentioned risks, researchers must carefully consider and minimize potential adverse effects of their activities to ensure ethical conduct. Guidance protocols and checklists have been developed for these purposes and should be consulted (Sandbrook et al., 2021; Sharma et al., 2020). In all cases, users should comply with the regulations, which are specific to the country, the drone's model and the type of mission. In the U.K. and Europe, regulations specify the type of licence a drone pilot must hold, with heavier drones and more complex operations requiring more advanced licences and restrict the flight modes and the areas where drones can operate. For example, special permissions/risk assessments are necessary to fly Beyond Visual Line of Sight or within the surroundings of airports or of protected natural areas such as national parks (Commission Delegated Regulation, 2019/945; Commission Implementing Regulation, 2019/947; U.K. Civil Aviation Authority, 2024). Moreover, institutional human ethical approval (in addition to nonhuman animal ethical approval) should be sought prior to data collection. In some cases, seeking the consent of people from whom data will be collected might be necessary, as would be expected for any research project involving humans. Users should also consider what would be done if drones unintentionally collected information on illegal activities (e.g. wildlife poaching) and the obligations that come with this. The specific risks and mitigations will vary with the context of the research. However, demonstrating that ethical issues associated with the use of drones have been considered and addressed appropriately is currently a requirement for publication in many leading behaviour and conservation journals (Sandbrook et al., 2023).

CONCLUSION

Drones will continue to transform the field of animal behaviour research, providing access to data in less accessible environments and enabling the study of common and elusive behaviours with minimal disturbance. The integration of advanced technologies for data collection (e.g. thermal imaging) and processing (AI) enhances their use, allowing for precise, noninvasive monitoring and manipulation of wildlife. These tools can also be combined with other observation methods (e.g. remote-sensing devices) to increase efficiency. However, the effective and ethical application of drones requires careful consideration of species-specific contexts, meticulous planning and a robust framework for data collection, management and analysis. By addressing these methodological and ethical challenges, researchers can harness the full potential of drones to deepen our understanding of animal behaviour and to improve conservation efforts.

Author Contributions

Lucia Pedrazzi: Writing – review & editing, Writing – original draft, Investigation, Conceptualization, Visualization. **Hemal Naik:** Writing – review & editing, Writing – original draft, Visualization. **Chris Sandbrook:** Writing – review & editing, Writing – original draft. **Miguel Lurgi:** Writing – review & editing, Funding acquisition, Project administration, Supervision. **Ines Fürtbauer:** Writing – review & editing, Funding acquisition, Project administration, Supervision. **Andrew J. King:** Writing – review & editing, Writing – original draft, Conceptualization, Supervision, Visualization, Funding acquisition, Project administration.

Data Availability

No data were used for the research described in the article.

Declaration of Interest

The authors have no conflicts of interest to declare.

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