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The Use of Drones for Studying the Behavior of Mammals

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Abstract—From their beginning unmanned aerial vehicles (UAVs) have been very useful in monitoring the abundance, distribution, and behavior of terrestrial and aquatic animals. At present, this technique is actively being applied to mammal research. The diversity and relative availability of drones allows for a variety of research tasks to be achieved. The advantages and disadvantages of UAV use are discussed in this review. The advantages of using UAVs in comparison to other methods are examined. New research opportunities opened up by drones are identified, and the advantages of modern analytical tools are emphasized. The technical limitations of UAVs and the problem of the negative impact of this technique on mammals are discussed. The need to minimize the disturbance of animals during such research is emphasized. In addition, this work summarizes the experience of using UAVs in studies on Russia's theriofauna.

Keywords: UAV, monitoring, observation, aerial filming

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INTRODUCTION

Modern biological research increasingly includes the use of various types of unmanned vehicles (flying, moving on various surfaces, underwater). Unmanned aerial vehicles (UAVs, drones, UASs) have become widely used in animal research and help to solve a wide variety of problems. In recent decades, UAVs, the application of which is the focus of this review, have changed and to some extent revolutionized the approach to animal observations by providing a platform for noninvasive study of certain aspects of species biology, including assessment of the abundance, distribution, and behavior of animals in their natural habitat (Schad and Fischer, 2022). The scope of application of UAVs is gradually expanding due to the constant improvement of both supporting platforms and attachments: from photo and video cameras of various spectrums to satellite navigation and positioning devices (López and Mulero-Pázmány, 2019). The use of UAVs to study animal behavior in their natural habitat is promising, primarily because it allows researchers to observe previously hidden types of behavior and change the perspective of the observation point, for example, to a view "from above." Drones can be used in hard-to-reach areas, in difficult weather conditions, etc., with minimal risk to researchers, while, as a rule, labor costs and the cost of collecting material are reduced.

The low cost combined with the high quality of the resulting material has contributed to the widespread use of UAVs. The drone can maintain sufficient altitude to conduct observations of several animals in a group simultaneously without degradation of the image quality due to interference such as clouds (Linchant et al., 2015; Xiang and Tian, 2011).

UAVs do not replace other methods of animal monitoring, as they have disadvantages: limited operating time (Pollock et al., 2022), dependence on weather conditions, and the noise they generate, which affects animals and their behavior (Christie et al., 2016). It is important that drones can only be used in open or semi-open areas. At present, civilian thermal imagers on UAVs, for example, cannot replace ground observations when studying forest species. This is partly possible in winter in deciduous forests, but at low temperatures the battery life is limited due to rapid discharge.

Currently, most researchers use UAVs to count the numbers of animals and assess their distribution (Corcoran et al., 2021; Schofield et al., 2019); to monitor populations of rare species; and as a means of preventing and combating poaching (Jewell et al., 2020; López and Mulero-Pázmány, 2019; Mulero-Pázmány et al., 2014). Quadcopter observations are also actively used to monitor farm animals, such as domestic bulls (*Bos taurus* L. 1758) (Mufford et al., 2019; Nyamuryekung'e et al., 2016; Mulero-Pázmány et al., 2015) and domestic sheep (*Ovis aries* L. 1758) (Al-Thani et al., 2020). These devices have proven to be particularly effective in studying the spatial dynamics of movement of individuals in groups (Maeda et al., 2021; Mufford et al., 2019) and recording previously unrecorded behavioral manifestations (Pollock et al., 2022). Drones have been most widely used in the study of mammals; it is this taxonomic group that has been the subject of most scientific research, in which animals were approached using UAVs (Mo and Bonatakis, 2022). Recently, drones have been increasingly used in behavioral research (e.g., Belikov et al., 2018).

The objectives of this review were to describe the variety of types of unmanned aerial vehicles and their use in modern zoological studies of mammals and to analyze the advantages and disadvantages of this method. Particular attention is paid to the negative impact of UAVs during scientific work on mammals and ways to minimize it. A separate section is devoted to the experience of using drones for research on mammals in Russia. This review is not aimed at a comprehensive disclosure of each of the topics under consideration; here, in a concise form, generalizations of the results of previous works concerning the study of various aspects of mammalian biology using UAVs are presented.

TYPES OF UAVS USED IN MAMMAL RESEARCH

The term "unmanned aerial vehicles" (UAVs) refers to the entire spectrum of autonomous aircraft: from small civilian ones to strategic ones weighing over 600 kg. In scientific research, small, inexpensive devices that are accessible to the civilian population are most often used (Fig. 1). The span of the propeller wings of such devices does not exceed two meters, on average, and the device is controlled by one operator (Lee, 2004). Small devices attract less attention from animals and therefore cause less disturbance (Lee, 2004).

The most commonly used UAVs in animal research can be divided into two categories: multirotor aircraft with propellers (copters) and fixed-wing (airplane-type) aircraft. Multirotor aircraft are capable of vertical take-off and landing, making them easier to use in areas with uneven terrain (Hardin and Jensen, 2011; Niethammer et al., 2012). They are capable of hovering in the air above an object and can be used to film the behavior of sedentary animals or, if necessary, to search for animals in a "complex" landscape that makes it difficult for the researcher to recognize the object visually. For example, an octocopter (UAV with eight rotors) was used in the development of a system for searching for roe deer fawns (*Capreolus capreolus* L. 1758) in fields before mowing, a stop in flight allowed the operator to examine the field and find the fawn hiding in the tall grass (Israel, 2011). However, in situations in which it is necessary to spend time searching for animals in advance, for example, secretive animals living in complex landscapes (for example, in forests) or having a very sparse population structure, one of the disadvantages of rotorcraft appears—the limited operating time of the copter, mainly 12–40 minutes (Colefax et al., 2018), which is due to the small battery capacity (Serin and Chur, 2022). In addition, the operation of copters depends on the meteorological conditions. It is not recommended to use a multi-rotor UAV in windy weather or during precipitation (rain, snow) (Grenzdörffer, 2013). Thus, multirotor devices are suitable for observing animals in preknown areas of concentrations or places of stay of individual individuals, as well as for short-distance flights, but they are not suitable for performing some search tasks.

Aircraft-type UAVs, in turn, are capable of flying long distances (flight time up to several hours). They have a higher flight speed, which is especially useful for animal surveys, as it allows one to obtain a picture of the location of individuals in a certain area in a short period of time and without the need for recharging (Mulero-Pázmány et al., 2014). The disadvantages of such UAVs are low maneuverability and the inability to hover over an object. In addition, some UAVs require special devices or platforms for launching and landing. For example, an aircraft used to monitor elephant populations was equipped with a high-frequency transmitter with a range of up to 180 km to locate the aircraft in the event of a GPS failure and required a flat, vegetation-free area of at least 150 × 30 m to land (Vermeulen et al., 2013). Accordingly, such devices are most effective for search tasks and for monitoring and counting of large animal populations.

Most UAVs use battery power to move their electric motors (Linchant et al., 2015). The advantage of this energy source is a lower noise level. Other devices use internal combustion engines (both to drive the propellers and to operate the electric generators); this provides longer flight times, for example up to 20 hours (Koski et al., 2009), but also creates a higher noise level and the risk of fire in such devices (Lee, 2004).

UAV control is often carried out in real time by an operator from the ground by a radio channel. Visual control of the flight is carried out either by direct observation of the device, which is in the operator's field of view, or, more commonly, remotely using a camera built into the UAV body, and taking into account flight telemetry data transmitted to the operator's console (Colefax et al., 2019; Kelaher et al., 2020). For some devices, it is possible to program the trajectory of its movement based on previously entered GPS points (often the operator can change such a route in real time).

The most commonly used suspended or built-in equipment of UAVs involved in animal research is visible-range photo/video cameras and thermal imagers (Linchant et al., 2015; Kostin, 2019). Visible cameras, even on small civilian UAVs, can produce a high quality image. Built-in cameras have the ability to stream video to the control panel or to the operator's smartphone connected to the drone. This allows one not

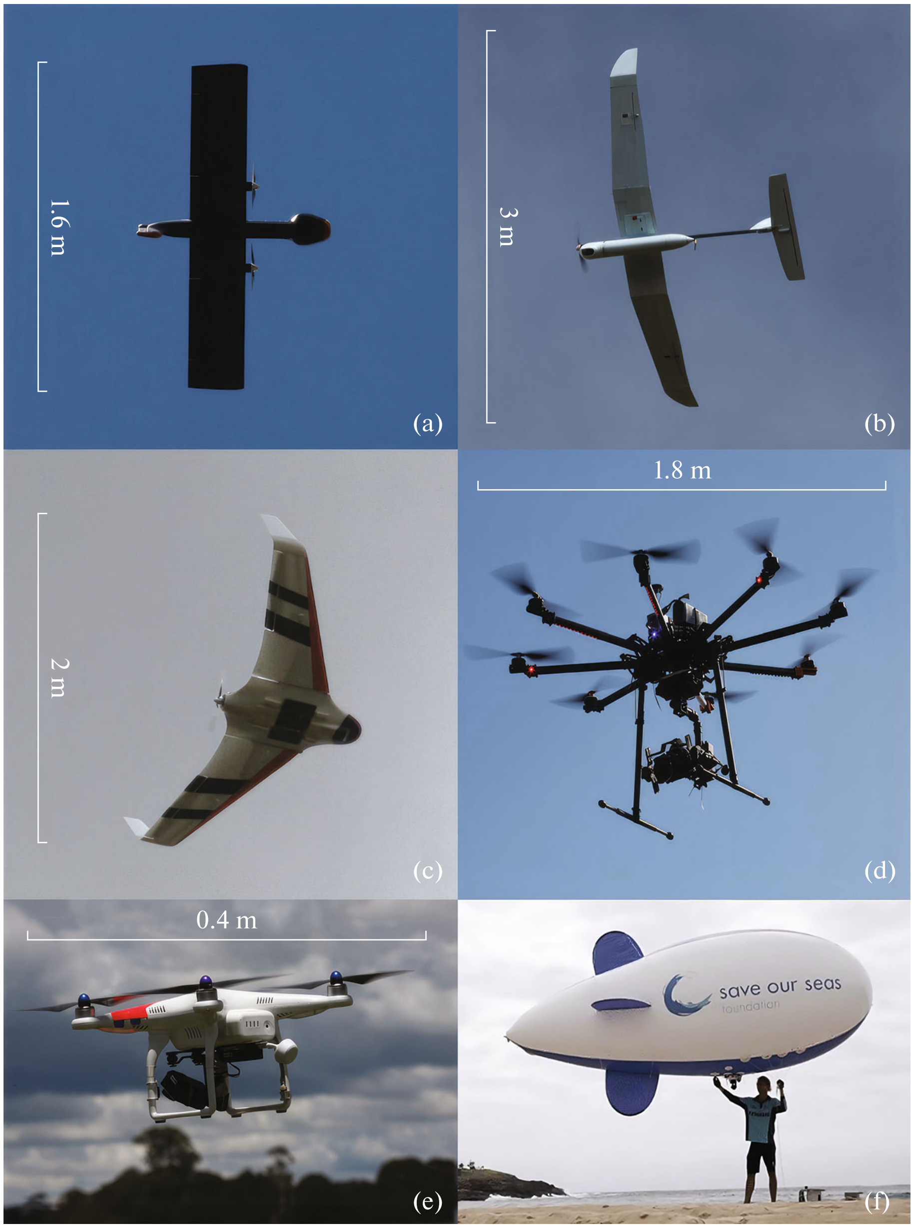

Fig. 1. Models of UAVs used for animal research: (a) fixed wing Avian-P, (b) fixed-wing Skylark II, (c) fixed wing and a pusher propeller Topodrone-100, (d) multi-rotor (octocopter) type Kraken-130, (e) multi-rotor (quadcopter) type Phantom, (f) like the Happy Win airship HWEA5202. The illustrations are under an open license for reuse: (a–d) according to McEvoy et al., 2016; (f) according to Adams et al., 2020.

only to control the flight, but also to shoot video and take photos during the flight. When filming video, the image quality is lower than when taking photographs (Mulero-Pázmány et al., 2014). The choice of a video camera is a compromise between cost, camera weight, and the minimum spatial resolution required for the study. For work in the dark, UAVs equipped with thermal imaging cameras are used (Israel, 2011; Mulero-Pázmány et al., 2014). Such equipment is applicable when the temperature of the underlying surface differs greatly from the body temperature of the animals being studied, which allows them to be distinguished from the background. However, thermal imaging cameras have a limitation related to the resolution of the sensors. For example, at a flight altitude of 150 m, using a camera with a matrix resolution of 640 × 480 pixels, it was possible to identify large species such as red deer (*Cervus elaphus* L. 1758) and wild boar (*Sus scrofa* L. 1758), and the success of the identification was influenced not only by the length of the body, but also by its shape, since the boars could be identified thanks to their head, which was almost invisible in low-resolution images, and their wide body. In turn, identification of roe deer at such a height was difficult due to their small body size; they could be confused with other, smaller animals or humans (Witczuk et al., 2017). Another limitation is the difficulty in identifying species of individuals with roughly the same size, such as the western gray kangaroo (*Macropus fuliginosus* Desmarest 1817), the eastern gray kangaroo (*Macropus giganteus* Shaw 1790), and the red kangaroo (*Osphranter rufus* (Desmarest 1822)), which could not be distinguished from one another in thermal imaging surveys conducted in Victoria, Australia (Lethbridge et al., 2019).

More nonstandard UAV suspension equipment options may also be used in mammalian research. For example, when studying cetaceans (Cetacea), hydrophones suspended from copters are used to record the acoustic signals of animals (Frouin-Mouy et al., 2020) and devices are used to capture the fountains formed by whale exhalations to determine the composition of their microbiota (Pirotta et al., 2017). A drone with a multispectral camera was used to develop methods for detecting polar bears against different types of backgrounds (Chabot et al., 2019).

Thus, existing UAV models, taking into account the possibility of their modification, make it possible to perform a variety of research tasks in a fairly wide range of environmental conditions. The main types of drones used in mammal research are multirotor and fixed-wing drones, each with its own advantages and disadvantages. The choice of UAV for each specific study should be made taking into account the characteristics of the objects of study (for more detail, see the section "The Impact of UAVs on Mammals") and the parameters of the data that need to be obtained.

ADVANTAGES OF UAVs FOR MAMMAL RESEARCH

An analysis of 169 research papers (not reviews) that approached wild animals using UAVs between 2000 and 2020 found that 95 papers studied mammals, 64 papers studied birds, 15 papers studied reptiles, and 15 papers studied elasmobranchs (Mo and Bonatakis, 2022). The widespread use of this relatively "young" method in studies of mammals is obviously associated with its certain advantages over other methods and approaches.

Advantages of UAVs over Other Methods

For many types of mammal studies, aerial filming is either the only possible method or the optimal way to collect material. For example, a top view of a large number of individuals is often necessary when conducting population censuses, studying the spatial structure of large aggregations, and observing rapidly moving groups of animals. Previously, a significant limitation for conducting such studies, for example from an airplane, helicopter, or balloon, was their high cost (Wang et al., 2019). One of the most important advantages of using small UAVs is their relatively low cost and, therefore, availability, especially in comparison with the use of manned aircraft. The variety of drone types allows one to select a device (choose the necessary technical configuration) for many research needs and a variety of budgets (Anderson and Gaston, 2013; Wang et al., 2019). The relative simplicity of the UAV design allows some researchers to fit and assemble them themselves, which also reduces costs and increases the speed of repair (Mesquita et al., 2021). In addition, to control a manned vehicle, it is necessary to involve additional specialists, while controlling a UAV (especially a rotary one) requires a minimum of special skills that a researcher can acquire independently.

An important advantage of UAVs over manned aircraft is the ability to fly at low altitudes, at which built-in cameras allow obtaining high-quality images (compared to images obtained from satellites) (Linchant et al., 2015; Xiang and Tian, 2011). The high quality of the resulting images (with a resolution of up to 4K on the ground) together with the ability to record video files with a high frame rate (up to 30 frames/s), allows researchers to determine the sex and age of animals (Mufford et al., 2019; Rathore et al., 2023), uniquely identify individuals (Pollock et al., 2022), and distinguish between different types of activity, including recording the environmental conditions surrounding the animals, such as the presence of conspecifics (Goldbogen et al., 2017; Torres et al., 2018). UAVs can be equipped with sensors that complement the images they receive, such as photographs taken in the infrared range (López and Mulero-Pázmány, 2019).

Drones have advantages over land-based, boat-based, or manned observations when surveying large aggregations or remote groups, providing greater accuracy in counting individuals, categorizing them, and identifying them (Hodgson et al., 2016, 2018). For example, when comparing the results of counts of California sea lions (*Zalophus californianus* (Lesson 1828)) from a boat and using UAVs, the use of drones allowed for the detection of a larger number of animals and a more accurate categorization of their age and sex (Adame et al., 2017). Counts of pups of the South African fur seal (*Arctocephalus pusillus doriferus* Wood Jones 1925) conducted with UAVs recorded 20–32% more individuals than ground-based counts (McIntosh et al., 2018).

An important advantage of UAVs compared to manned aircraft is their small size and low noise level. This helps to minimize the impact of drones on animals and their behavior if researchers follow certain guidelines for filming animals, such as maintaining a sufficient height, taking into account wind direction and noise propagation (Christie et al., 2016; Ditmer et al., 2015). Some animals quickly become accustomed to the sound of drones filming. A targeted study of the habituation rate of American black bears (*Ursus* *americanus* Pallas 1780) kept in captivity to UAV overflights demonstrated that bears became accustomed to such a new stimulus within a relatively short period of time (three to four weeks). At the same time, animals kept in captivity are generally more tolerant of any human intervention (Ditmer et al., 2019). Cattle showed habituation to UAV overflights over three days in a study designed to investigate the spatial structure of groups (Mufford et al., 2019). The habituation of mammals to UAVs in the wild requires further research. Different drones produce noises of different intensities and in different frequency ranges depending on the size of the propellers, the type of engine, and other parameters. Selecting the most suitable UAV type in terms of its noise characteristics for studying specific species may be a promising direction for future work in this area.

An additional advantage of using UAVs in mammal research is its relative safety for the researcher. Manned aircraft crashes are a common cause of death among field biologists in the United States (Sasse, 2003). It is also obvious that the use of UAVs is much safer than direct observation of animals, such as polar bears (*Ursus maritimus* Phipps 1774) (Jagielski et al., 2022). In addition, the movement of the researcher in hard-to-reach places where some species live can be dangerous (Christie et al., 2016; Linchant et al., 2015). Thanks to the remote control of UAVs, these threats can be avoided; some drones can move away from the operator over a distance of up to several kilometers (Hughey et al., 2018).

It can be concluded that UAVs have a number of obvious advantages over other more traditional methods of collecting material. The relative affordability of drones is coupled with the ability to produce high-quality images. The accuracy and information content of data obtained using UAVs often exceeds that obtained using other traditional methods of counting and observing mammals. Important advantages of drones over manned aircraft are the low noise level and relative safety for the researcher.

New UAV Capabilities

The use of UAVs allows for detailed and comprehensive studies of mammals that have not been conducted before. For example, the parallel use of two copters—one with a suspended hydrophone and the second equipped with a standard visible spectrum camera—made it possible to obtain unique data on the relationship between the behavior and acoustic signals of gray whales (*Eschrichtius robustus* Lilljeborg 1861) and the parameters of these signals: the sound source, its frequency, and the time characteristics (Frouin-Mouy et al., 2020). In an experiment designed to study alliance formation in male Indian bottlenose dolphins (*Tursiops aduncus* (Ehrenberg 1833)), the UAV filming was carried out synchronously with an underwater speaker, with which the researchers reproduced individual signals (whistles) of males and recorded reactions in the group, short-term and visible only from above (King et al., 2021). A nonsinking multi-rotor UAV (Figs. 2a, 2b) was also used to collect material from the exhalation fountains of humpback whales (*Megaptera novaeangliae* Borowski 1781) on their migration route near the coast of Australia (Pirotta et al., 2017). Based on the material collected, it was possible to determine with high accuracy the composition of the microbiota of the whale's exhalation, which reflects the health of the animal, and parallel photography ensured the separate identification of each individual studied. The condition of the whales was also monitored using drone images. Using a 3D whale body model and data on the size characteristics of the species, the authors calculated the estimated body volume and mass of each individual photographed from the air (Christiansen et al., 2019).

A special feature of rotary UAVs is their ability to hover over the observed object. This allows animal behavior to be recorded with high accuracy and detail. For example, in a study of the behavior of wild dingoes (*Canis lupus dingo* (Meyer 1793)) using a quadcopter, the characteristics of dingoes hunting for representatives of the kangaroo family (Macropodidae) were recorded for the first time and a detailed description of the interactions between a mother and a baby dingo during a joint hunt was made (Pollock et al., 2022). Filming from a quadcopter made it possible to study in detail the parasitism of kelp gulls (*Larus dominicanus* Lichtenstein 1823) on southern right whales (*Eubalaena australis* (Desmoulins 1822)) and the response to avoid such parasitism (Azizeh et al., 2021).

In recent years, drones have been used to study mammals the biology of which was previously difficult to study, such as bats (Chiroptera). For example, a device was developed with a system of devices, including a spherical microphone, that physically isolates the noise of the UAV and records both the ultrasonic signal of bats and their three-dimensional thermal signature during flight (Fu et al., 2018; Fig. 2c). The use of a drone with a thermal imager also allowed a detailed study of the distribution of colonial gray-headed flying foxes (*Pteropus poliocephalus* Temminck 1825) while resting in trees (McCarthy et al., 2021).

Thus, UAVs provide broad opportunities for solving nonstandard scientific problems and allow us to study little-studied aspects of the life of mammals in nature.

Automation of Analysis of Survey Materials Using UAVs

As UAV filming becomes more widely used in scientific work, huge amounts of data are often accumulated that require subsequent processing. In order to avoid significant costs of working with such materials "manually," various automated or partially automated analytical tools are actively being developed. The

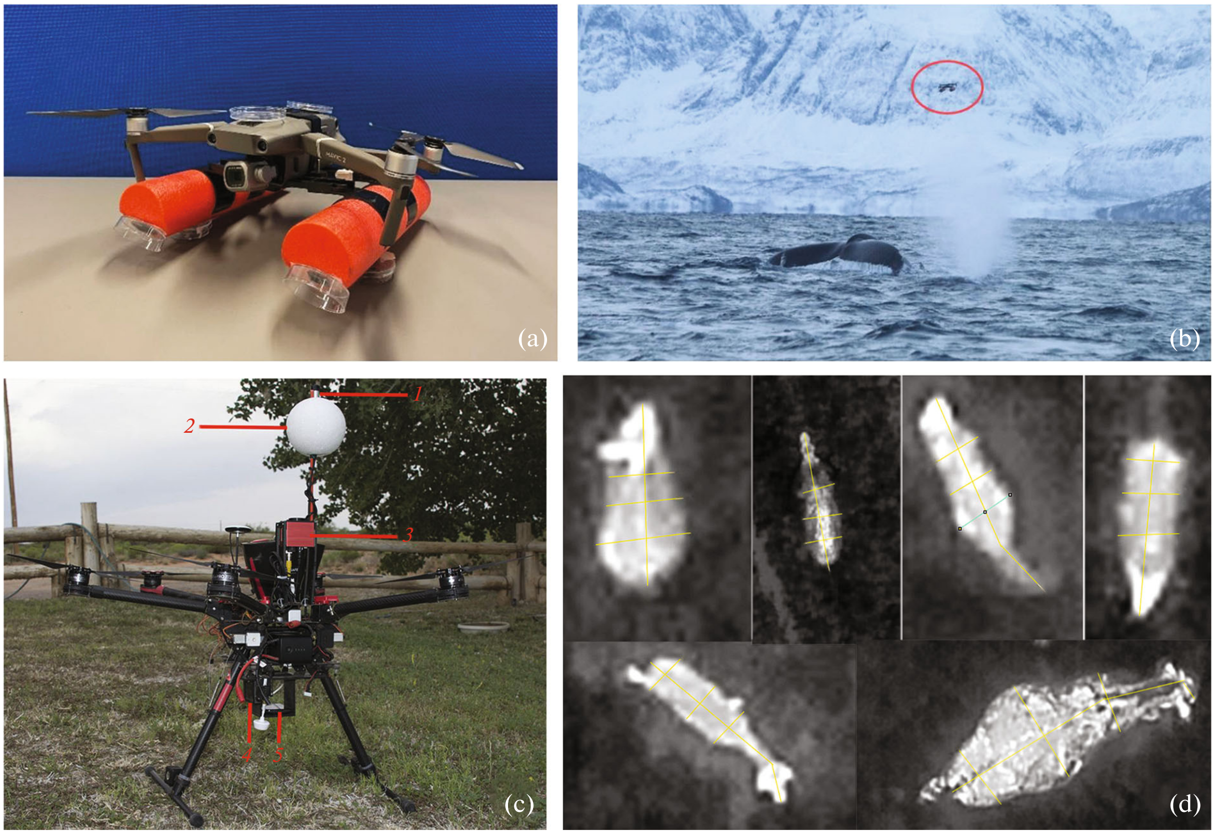

Fig. 2. UAV with additional capabilities in addition to standard shooting. Study of microflora from the exhalation of a humpback whale: (a) a modified DJI Mavic Pro 2 drone with foam floats and six attached Petri dishes for (b) taking a sample (the drone in flight is indicated by a red circle). (c) Modification of the DJI Spreading Wings S900 hexacopter for recording bat ultrasound with parallel thermal video filming: (*1*) ultrasonic microphone ULTRAMIC250K, (*2*) a foam ball to absorb the sound of the rotors, (*3*) thermal imaging camera, (*4*) recorder for recording thermal imaging videos and (*5*) a recorder for recording sounds from bats. (d) The use of a thermal imager to study different species of terrestrial mammals at night, where species were successfully determined based on body proportions in heat trace images. From left to right, top row: hare, red deer, marten, badger; bottom row: roe deer and cow. The illustrations are under an open license for reuse: (a, b) Costa et al., 2022; (c) Fu et al., 2018; (d) Larsen et al., 2023.

availability of successfully applied ready-made solutions and the constant emergence of new developments in the field of automated analysis of photo and video material obtained using UAVs is a great advantage of using drones.

An example of the effective use of automated mammal identification algorithms is the study of hippos (*Hippopotamus amphibious* L. 1758) when filming with a thermal imaging camera installed on a UAV. The number of individuals in the water was calculated as follows: the algorithm compared the body length of the animal being studied in the infrared images with the template body length of the hippopotamus in pixels specified by the researcher. The program identified hippos in photographs with an average error of 2% compared to manual identification, making it a worthy alternative to human counts (Lhoest et al., 2015).

A more sophisticated method, object-based image analysis, uses an algorithm to segment spectrally similar pixels, resulting in a mosaic of closely spaced objects, each of which receives its own classification. This approach has shown higher efficiency in identifying animals in UAV images than previous algorithms (Corcoran et al., 2021). This type of analysis is supported by the Trimble software (eCognition Developer 8.7), which has proven effective in identifying and counting large mammals in a multispectral (visible and infrared) video. The program did a better job of identifying larger bison and wapiti (*Cervus canadensis* (Erxleben 1777)), while wolves (*Canis lupus* L. 1758) and fallow deer (*Dama dama* (L. 1758)) were determined with less efficiency. The authors explain this by the cryptic coloration of the fur of the latter, smaller body sizes, and also by the fact that, in a combined analysis of thermal imaging and conventional surveys, the temperature contours of heated stones and open soil could coincide with the contours of the animals (Chrétien et al., 2015). This technique has also been shown to be effective in recognizing white-tailed deer (*Odocoileus virginianus* (Zimmermann 1780)) (Chrétien et al., 2016).

Another algorithm (detection of moving wild animals) is based on the comparison of several images obtained by a flying UAV and was created to register the movements of wild animals. By comparing a series of images, artificial intelligence identifies objects that have changed their position and moved to the next position. This method was used to count spotted deer with an accuracy of 77.3% (*Cervus nippon* Temminck 1838) in Nara Park, Japan, and the algorithm even outperformed humans in accuracy, who detected only about 30% of the individuals (Oishi et al., 2018). However, the authors of this study note that this algorithm is only applicable in open areas or in areas covered by sparse forests, since, for example, the movement of tree tops due to wind can also be read by the algorithm as animal movements.

Convolutional neural network algorithms, unlike the simpler algorithms described earlier, use the spectral characteristics of a pixel and its proximity to other pixels, combine this information into a matrix that is used to extract certain "characteristics" of an object, and then determine the similarity of objects in the image based on the proximity of these characteristics (Corcoran et al., 2021). A highly accurate neural network, working with images of large and medium-sized mammals taken from a drone in a reserve in Namibia, was able to determine the species of animals of more than 20 species. Producing results at 72 images per second, the algorithms proved effective for real-time monitoring. At the same time, the ultra-precise neural network is much less dependent on the characteristics of the background against which the animals were filmed (Kellenberger et al., 2017). The use of active learning (AL) algorithms has greatly improved the efficiency of this software in the search for large ungulates by reducing labor costs for training the neural network. To train the algorithm, a person needed to view only 0.5% of the images, and the efficiency of the neural network in identifying animals reached almost 80% (Kellenberger et al., 2019).

Automated methods for analyzing UAV images are not limited to the goal of actually detecting animals. To date, both individual automated programs and complex software (SW) have been developed that perform the labor-intensive work of sorting, identifying and tracking the trajectory of individual individuals, classifying social contacts, measuring and tracking the distance between individuals (Fig. 3), etc. Automatic construction of orthomosaics from a series of UAV images made it possible to analyze the relative positions of individuals and to describe the social structure in herds of cattle (Mufford et al., 2019) and feral horses (Maeda et al., 2021).

The Ethoflow software uses algorithms for species identification, tracking the movement of individuals and their behavioral acts on video recordings made from above. This software has great potential for use with UAVs. For example, using Ethoflow, close contacts between individuals can be identified from video recordings (Bernardes et al., 2021). The DeepPoseKit software, which uses deep learning algorithms, has proven effective in recognizing the body positions of individuals in a variety of settings, including in groups and when individuals interact with each other. This software was tested on video recordings of Grevy's zebras (*Equus grevyi* Oustalet 1882), in which it effectively determined the position of the individual's body at a very high speed (Graving et al., 2019). The position of Grevy's zebras when moving in a herd was also analyzed using computer vision algorithms, which were able to build a 3D model of the surrounding space based on video recordings from a quadcopter using key points and to analyze the movement of individuals within this space. The software used not only created tracks of individuals, but was also able to track their direction and individual movements using key points on the body. The software was also effective in tracking the movements of the terrestrial primates gelada baboons (*Theropithecus gelada* (Rüppell 1835)) (Koger et al., 2023).

Thus, today there are many successful developments in the field of automation of various elements of analysis of photo and video material obtained using UAVs. Researchers conducting UAV surveys are provided with ample opportunities to work with large volumes of data at a relatively low cost in terms of labor and time.

DISADVANTAGES OF UAVs FOR MAMMAL RESEARCH

Technical Limitations

UAVs have a number of technical limitations that may negatively impact their applicability in scientific research (Anderson and Gaston, 2013). One of the significant disadvantages is the relatively small battery capacity and, accordingly, the limited operating time of the drone. For example, in a study of dingo hunting behavior, the operating time of a quadcopter was only 27 min under ideal weather conditions, and at low temperatures the operating time was reduced to 20 min (in some situations, the end of the behavioral act could not be recorded) (Pollock et al., 2022). In addition, a direct comparison of the data obtained from the study of African bush elephants (*Loxodonta africana* (Blumenbach 1797)) using a fixed-wing UAV and a conventional aircraft showed that UAV flights are limited to transects of 40 km in length maximum, compared to transects of 1000 km in length that can be covered by a manned aircraft (Vermeulen et al., 2013). The battery life of a UAV may also be reduced when additional equipment such as heavy cameras, transmitters, or microphones is required.

UAVs used in zoological research cannot be called universal; external conditions largely limit the possibilities of their use. Thus, in strong and gusty winds,

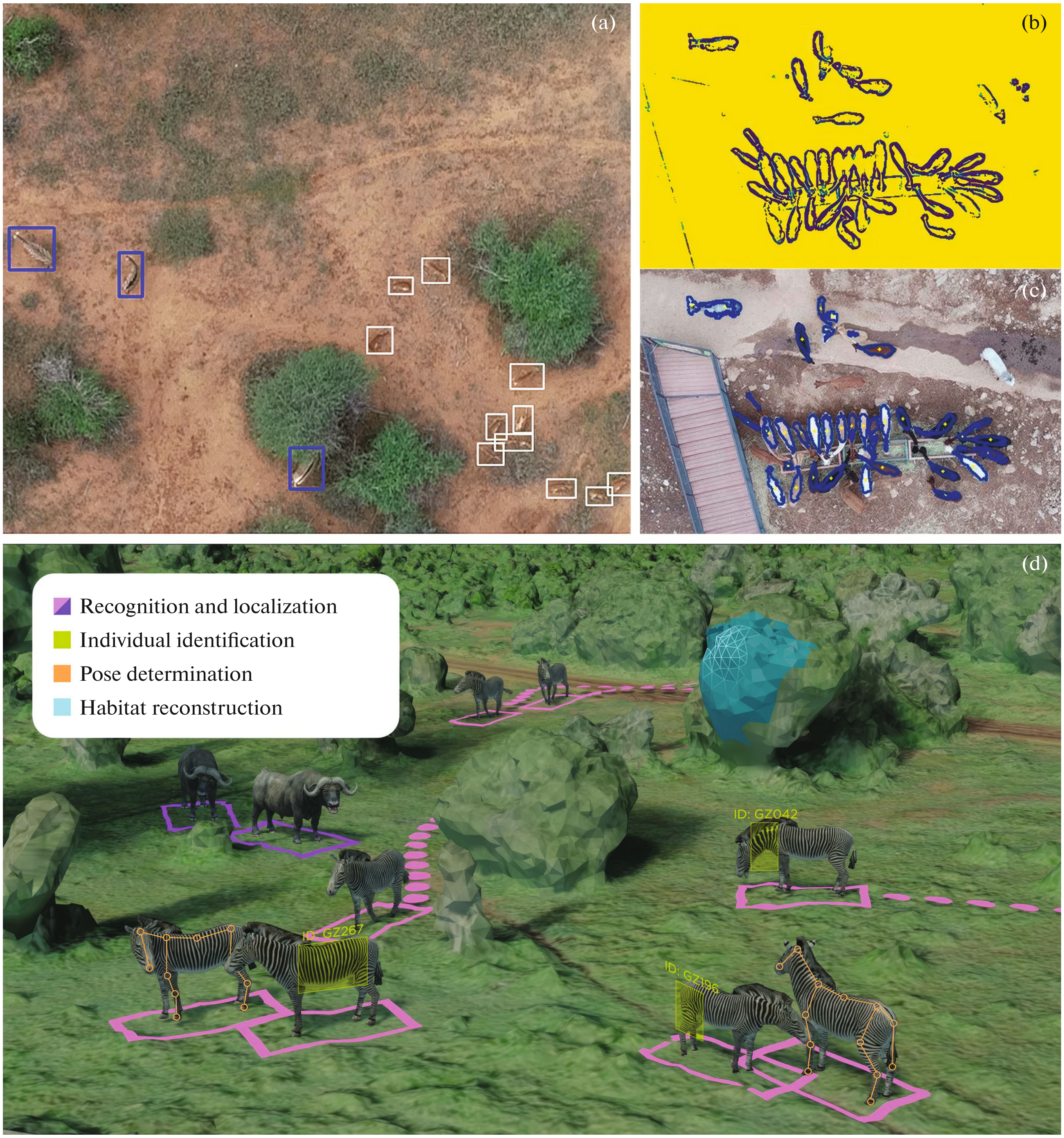

Fig. 3. Using computer vision algorithms to analyze materials obtained from UAVs. (a) Simultaneous automatic detection and tracking of two ungulate species with visualized object bounding boxes (bbox) for two video frames using trained models (zebras, blue; impalas, white). An example of automatic detection of animals on a complex background (b) using the Sobel operator function for edge detection and (c) their rendering onto the original image. (d) A summary infographic demonstrating modern capabilities of using computer vision for recognizing the species of mammals and their position in space (purple), tracking their movements (pink), individual identification of individuals (green), categorization of body postures (orange), and reconstruction of habitats, including damaged ones (blue). The illustrations are under an open license for reuse: (a) Koger et al., 2023; (b, c) Lee et al., 2021; (d) Tuia et al., 2022.

the UAV may lose control and crash (Weissensteiner et al., 2015). Other adverse weather conditions, such as precipitation or simply high humidity that leads to fog and fogging of sensors, can hinder the use of drones. Despite the ability to fly over a variety of terrains, including those difficult for humans and ground vehicles to navigate, most drones require a flat surface for takeoff and landing (Anderson and Gaston, 2013).

Poor performance of cameras and stabilizers can negatively impact the quality of images obtained by UAVs. In flight, image stabilization may be difficult due to vibrations generated by the engines and rotors, and the image itself may be marred by artifacts such as oversaturation, vignetting, chromatic aberrations, and improper color balancing (Whitehead and Hugenholtz, 2014).

UAVs are practically unusable for filming the behavior of some species of mammals. For example, most UAVs are considered unsuitable for studying small animals (weighing less than 30 kg); they are too difficult to recognize from an altitude at which flying will not disturb the animals (Hughey et al., 2018). The environment in which a particular species lives may also place restrictions on the use of drones. Trees with dense canopies or murky water make detecting animals a nearly impossible task. However, in such situations (if we are talking about warm-blooded animals), thermal imaging cameras should be used (Fig. 2d). For example, when counting large representatives of the kangaroo family (Macropodidae) in the forests of Australia using images from thermal imaging cameras, it was possible to detect 30% more individuals than without the use of special equipment (Lethbridge et al., 2019). The resolution of thermal imaging cameras can be a significant limitation. Therefore, the researchers recommend using thermal imaging cameras with a resolution of at least 1024 × 768 pixels to identify small animals and note that even such cameras may not be effective in forests with a large number of trees with dense canopies. In such forests, the use of any aircraft is still inferior in efficiency to ground-based observations (Witczuk et al., 2017).

It is important to mention that there are restrictions on the use of UAVs established in most countries of the world at the legislative level. In Russia, such regulation is carried out by the Air Code of the Russian Federation of March 19, 1997, no. 60-FZ, which requires mandatory certification of drones weighing 30 kg or more and their registration with a weight of 0.5 to 30 kg in accordance with the Decree of the Government of the Russian Federation of May 25, 2019, no. 658.

Among the limitations associated with the technical characteristics of UAVs and negatively affecting their applicability and the quality of the data obtained, one can highlight the relatively small capacity of batteries, the presence of certain requirements for shooting conditions, and the need to take into account the characteristics of the landscape in which the animals being studied are located. However, many of these limitations can be compensated for by adjusting the device, using additional equipment, and, in part, by the operator's experience.

The Impact of UAVs on Mammals

With the increasing use of UAVs as a promising method for studying mammals, reports have emerged of avoidance reactions and signs of distress caused by the proximity of drones among the observed animals. Terrestrial and aerial animals most commonly exhibit changes in normal behavior in response to an approaching UAV. Many large terrestrial mammals studied display a behavioral response to the flight of a UAV, most frequently reactions of fleeing or heightened alertness. According to research on the reactions of seven large terrestrial herbivores—savannah elephants, giraffes (*Giraffa camelopardalis* L. 1758), blue wildebeest (*Connochaetes taurinus* (Burchell 1823)), plains zebras (*Equus quagga* Boddaert 1785), impalas (*Aepyceros melampus* (Lichtenstein 1812)), antelopes (*Kobus leche* Gray 1850), and topis (*Damaliscus lunatus* (Burchell 1824)). All species exhibited negative behavioral responses, primarily fleeing (Bennitt et al., 2019). Avoidance reactions were observed more frequently in open areas than among trees, which the authors attribute to differences in the predator response strategies depending on the environment: in forests, remaining still is a more advantageous strategy against an approaching ambush predator, as fleeing inevitably generates noise and increases the risk of injury due to the presence of numerous obstacles (Bennitt et al., 2019).

The sound emitted by UAVs appears to be the most significant source of disturbance to mammals. Nocturnal animals like the southern hairy-nosed wombat (*Lasiorhinus latifrons* (Owen 1845)) responded by fleeing to the sound of a drone at night, when they most likely could not see it (Headland et al., 2021), and large African herbivores demonstrated a behavioral response to a UAV before the device appeared in their field of vision (Bennitt et al., 2019). An approaching rotor drone may sound like swarming bees, which can sting even large mammals, and therefore scare away animals, especially elephants (King et al., 2017). To minimize stress that may occur in large terrestrial mammals when approached by a UAV, it is recommended to maintain a flight altitude of more than 60 m and a horizontal distance of more than 100 m (Bennitt et al., 2019). Similar recommendations are given by researchers who assessed the reaction of giant kangaroos to the approach of UAVs. Maintaining a flight altitude of 60 m or more reduced the visible disturbance of the animals to a minimum. Flight at 30 m elicited a very intense flight response, so such low flights should not be performed in studies of terrestrial mammals (Brunton et al., 2019).

The species of the mammals studied may influence the severity of their reaction when a drone approaches. A comparison of the level of disturbance from UAVs in large African herbivores showed that the least pronounced response was in impalas and lechwe antelopes, which may be due to the comparatively weak hearing of these species (Bennitt et al., 2019). However, for unknown reasons, Burchell's zebras and blue wildebeests showed the most intense avoidance response when approached by a drone, which is why the authors recommend not using drones at all to study these species (Bennitt et al., 2019). A comparison of data from UAV-based and ground-based diversity surveys of bat species showed that fewer species were recorded in the same locations using UAVs. The UAV appears to have disturbed species that were most sensitive to its noise, and these species were not included in the census data (Ednie et al., 2021).

The age and sex category to which an animal belongs can also influence the intensity of the reaction to a UAV. Przewalski's horses (*Equus ferus przewalskii* (IS Polyakov 1881)) fled when the drone approached. The severity of the reaction depended on the sex and age of the individual: adults were more vigilant (on average, they started to run away when the UAV was at an altitude of about 20 m), while males responded to the UAV that was at a higher altitude, which is presumably related to the role of males as protectors of the group (Lu et al., 2021).

An additional factor that determines the severity of the reaction to the approach of a drone may be the social environment of the animals. Thus, the average startle distance for solitary guanacos (*Lama guanicoe* (Müller, 1776)) is 154 m, while for groups it is 344 m. Large groups of guanacos responded to drones earlier than small groups. Presumably, this may be due to the higher chances of noticing a threat in larger groups (Schroeder and Panebianco, 2021).

Drones can cause not only obvious avoidance responses to observers, but also subtle behavioral effects by influencing the time animals spend feeding, social interactions, resting, and moving. When a fixed-wing UAV flies at an altitude of 120 m, feral horses (*Equus ferus caballus* L. 1758) spent less time resting and grooming and more time on feeding, moving, and being alert. Bisons (*Bison bison* (L. 1758)) also spent less time resting and grooming and more time feeding and moving when UAVs monitored them. However, the animals did not show any avoidance reactions. Thus, in some cases, the UAV may be perceived as a source of relatively small risk, not enough to cause flight, but which leads to a change in behavior and possibly allows coping with stress (Lenzi et al., 2022).

In addition to behavioral changes, approaching UAVs may also induce stress-related physiological responses. Such reactions, especially if prolonged and/or regular, can reduce the overall fitness of the individual without the researcher being aware of the damage being caused to the animal. A stress physiological response, an increase in heart rate, was recorded in black bears when a quadcopter approached, although a visible behavioral response was uncommon (Ditmer et al., 2015). Interestingly, a similar reaction has been shown not only in mammals: king penguins (*Aptenodytes patagonicus* J.F. Miller 1778) also showed a significant increase in heart rate when approached by a drone, without any changes in behavior (Weimerskirch et al., 2018). Thus, even without causing visible avoidance reactions, UAVs can be a source of stress for animals.

The impact of drones on mammals can vary depending on whether the animals are on land or in aquatic environments. Terrestrial mammals tend to alter their normal behavior more significantly when drones approach (Schroeder et al., 2020; Pomeroy et al., 2015; Smith et al., 2016). This is due to the fact that visual and acoustic signals from drones penetrate aquatic environments less effectively. In coastal areas, the sounds of rotor UAVs are not louder than the environmental background noise, and in other locations, these sounds are barely audible at flight altitudes of 5–10 meters above the surface of the water, and only to animals located at a depth of about one meter. Among marine mammals, baleen whales (Mysticeti) and northern elephant seals (*Mirounga angustirostris* (Gill 1866)) reacted to the sound of drones only in low-noise environments (Christiansen et al., 2016). Bottlenose dolphins (*Tursiops* sp.) displayed behavioral changes (increased frequency of specific behaviors, particularly diving) in response to a descending drone, as they swam close to the surface of the water where they could hear it (Giles et al., 2021). Beluga whales (*Delphinapterus leucas* (Pallas 1776)) in the St. Lawrence estuary exhibited avoidance behaviors or increased agitation only when UAVs flew below 23 meters (Aubin et al., 2023). Among members of another mammalian order, Sirenia, sea cows (*Dugong dugon* (Muller 1776)) did not show significant reactions to fixed-wing drones with internal combustion engines, which produce noise similar to rotor UAVs (Hodgson et al., 2013), whereas captive West Indian manatees (*Trichechus manatus* L. 1758) exhibited pronounced reactions to drones (Landeo-Yauri et al., 2021).

According to the results of a study of semi-aquatic mammals, such as sea otters (*Enhydra lutris* (L. 1758)) and some species of pinnipeds (Pinnipedia), the approach of UAVs had the greatest negative effect when the animals were out of water, where the noise from the UAV was more audible (Pomeroy et al., 2015; Smith et al., 2016). For example, Ladoga ringed seals (*Pusa hispida ladogensis* (Nordquist 1899)) leave their rookeries for the water when a rotary UAV approaches, even if the pilot maintains a relatively high flight altitude of 150 m (Medvedev et al., 2017).

Thus, the significant amount of factual material accumulated to date demonstrates that the use of UAVs near mammals has a negative impact to one degree or another on most species. However, on land this impact is greatest. It is important to take into account that the anxiety of mammals in response to the approach of a drone may be barely noticeable to the observer and only causes a change in the physiological indicators of the animals.

Suggestions for Minimizing the Negative Impact of UAVs

The above examples of negative impacts on mammals indicate the need for a balanced and limited use of drones by researchers, filmmakers, photographers, and tourists. Based on the experience accumulated to date in conducting research on mammals using UAVs, it is possible to formulate basic principles, guided by which researchers can reduce to a minimum the negative aspects of using UAVs. The ethical standards being developed for the use of UAVs to film wild animals include recommendations to avoid disturbance and active pursuit of animals (Fedorova, 2021).

Taking into account the literature data on the impact of UAVs on mammals, it is worth conducting filming at the maximum possible distance from the animals. The optimal strategy is to conduct test flights before actually collecting data using UAVs. Test flights will help determine the flight altitude threshold at which the UAV remains undetected by animals or causes only minimal alarm reactions (Saitoh and Kobayashi, 2021). It is worth noting that the available literature data on the distance at which a drone can startle individuals of a particular population may not be applicable to other populations of the same species, as the reactions of animals may depend on their previous experience. For example, animals that constantly live near humans may be more accustomed to anthropogenic noise sources, while the reaction of individuals from another population living in places far from humans may be much more pronounced. However, even a small reaction does not mean the absence of physiological stress (Ditmer et al., 2015). It is almost impossible to predict the impact of this process on the survival of an individual and the group being studied, but it is worth considering the possibility of such an effect and direct intervention in the course of the life of an animal should be carried out only in the absence of other possible ways of studying a particular phenomenon (Ditmer et al., 2015; Weimerskirch et al., 2018). The use of low-noise or silent UAVs (aerostats) can help to avoid a pronounced effect on animal behavior. To minimize the negative impact on animals, it is necessary, for example, to calculate the minimum necessary values: the duration of filming, the number of individuals filmed, the frequency of flights in the same area, etc. Another important recommendation is to select the optimal time of day for filming. In hot weather, it is logical to limit flights to morning, evening, or night hours, when there is a lower risk of overheating of animals (both the direct objects of research and those disturbed in the course of the work) in the event of an active avoidance reaction to the UAV. In addition, when planning work, it is necessary to take into account the species characteristics of the animal and the environment in which it is located (Bennitt et al., 2019; Pomeroy et al., 2015; Smith et al., 2016).

EXPERIENCE OF USING UAVs IN MAMMAL RESEARCH IN RUSSIA

As in other countries, in Russia the use of UAVs has become especially widespread in marine mammal research. This method, with relatively low financial costs, allows one to survey vast territories/water areas, register animals in hard-to-reach places, and obtain the optimal angle for observations, which is especially important when working with marine mammals.

Using a quadcopter, population counts of Pacific walruses (*Odobenus rosmarus divergens* Illiger 1811) were conducted at Cape Vankarem, where land-based observations are challenging due to the lack of vantage points. Experimental studies identified the minimum safe altitude (60–70 m) from which drone surveys of walruses could be conducted without disturbing them (Skorobogatov et al., 2020). A similar issue of inaccessibility for research existed at haul-out sites for Pacific walruses in Keniskin Bay (Chukotka), where the use of drones allowed for successful population counts and spatial distribution assessments (Altukhov et al., 2020). Additionally, drone-based population counts of Steller sea lions (*Eumetopias jubatus* (Schreber 1776)) were carried out successfully on Mednyi Island. Drones provided an advantage in the quantity and quality of the data collected compared to more labor-intensive traditional methods. The sea lions did not show any visible reaction to the quadcopter flying at an altitude of 20–30 m (Laskina et al., 2020). Another example of using drones to study pinnipeds is the survey of Baikal seal (*Pusa sibirica* Gmelin 1788) haul-outs on the shores of Lake Baikal (Protected Area Zapovednoye Podlemorye). In addition to counting the seals, the authors determined the disturbance distance upon drone approach. The animals exhibited signs of disturbance when the drone descended to an average height of 11 m, although this distance increased when the seals were resting in groups (Ivanov et al., 2022).

Cetacean (Cetacea) research also increasingly involves the use of UAVs. Four types of drones were used to conduct population censuses and to observe the behavior of the White Sea and Anadyr beluga whale populations (Belikov et al., 2018). Using a fixed-wing UAV, the population size of individuals in a reproductive aggregation near Bol'shoi Solovetskii Island was assessed. Moreover, the results of this survey were consistent with the data of traditional coastal observations. In addition, new patterns of territory use by beluga whales were established. For example, a shift in the preferred aggregation site of individuals to the southern part of the accumulation territory was determined. New information was also obtained about the timing of beluga whale visits to the study area in relation to the tidal dynamics. Coastal observations previously allowed tracking belugas only at low tide, while drone footage has shown that belugas can be found in the aggregation area at high tide as well. Rotary UAVs have proven effective for beluga whale research, but they have been noted to impact beluga whale behavior. Filming of gray whales from UAVs made it possible to supplement existing catalogues of individual markers of individuals with photographs of the dorsal side of the body of these animals (Tyurneva et al., 2019). In addition to photo-identification materials, the drone provided data on the behavior of whales, which made it possible to determine the exact age at which the calves began feeding and began to forage independently, as well as to describe the feeding behavior of adults. During observations of carnivorous killer whales (*Orcinus orca* (L. 1758)) near the Commander Islands, it was possible to record the peculiarities of their behavior when hunting northern fur seals (*Callorhinus ursinus* (L. 1758)) (Bychkov et al., 2021).

The use of UAVs to study the theriofauna of Russia is not limited to marine mammals. Although to a lesser extent, this method is also gaining popularity in studies of terrestrial mammals. For example, a method for conducting censuses of game animals using UAVs has been proposed, where the effectiveness of this method of census due to the savings in time and resources has been noted. For such work, it is recommended to combine surveys in the visible and IR spectrum to obtain objective data on the numerical and age–sex composition of groups of individuals (Grekov, 2018). A moose (*Alces alces* (L. 1758)) census in Yaroslavl oblast showed the high efficiency of a census using UAVs; however, the authors note the labor intensity of processing a large number of images in the case where the census area is large (Morgunov et al., 2019). Combined imaging in the visible and infrared spectrum was used to record the presence of bison (*Bison bonasus* (L. 1758)) in certain areas of the Orlovskoye Polesie National Park at night. The authors note the applicability of this research method on par with conventional observations (Prigoryanu et al., 2021). The UAV has proven its effectiveness in studying polar bear maternity dens on Wrangel Island, as it made it possible to assess fairly accurately the location of the dens from a long distance with minimal disturbance to the female and cubs, to describe them in detail, and to characterize the family group occupying this den, while avoiding risk to observers (Vasiliev et al., 2021). UAVs were also effective in collecting indirect signs of the presence of animals (trails, beds, etc.) in protected areas (Medvedev et al., 2015; Prigoryanu et al., 2021). Filming the gazelle (*Gazella subgutturosa* (Güldenstädt 1780)) from a rotary UAV made it possible to study the characteristics of group behavior of animals when avoiding danger (Berezina, 2021).

Thus, in Russia, the use of UAVs (unmanned aerial vehicles) in biological research is still somewhat behind in scale compared to international efforts. However, an increasing number of researchers is incorporating drones into their scientific work. Successful research experiences demonstrate that UAVs allow for optimization of population counts, exploration of previously inaccessible populations and habitats, and documentation of previously unknown behavioral characteristics. Russia has vast untapped potential for using UAVs in the study of mammals. For example, drones can become an effective tool to facilitate research work in the harsh conditions of long Siberian winters with extremely low temperatures, enabling the monitoring of sparse populations of large warm-blooded animals such as moose, Siberian roe deer (*Capreolus pygargus* (Pallas 1771)), and wolves (Prosekov et al., 2022).

CONCLUSIONS

The results of the scientific papers reviewed in this review, for which the material was collected using UAVs, demonstrate the applicability and effectiveness of drones in research involving mammals. The diversity of UAVs and their use options allows for a wide range of research tasks to be performed in a variety of conditions. The popularity of this technology among researchers is due to a number of advantages it has over other methods of collecting material. The availability and ability to modify and independently use UAVs makes aerial filming much more accessible to researchers. The high quality of the resulting images ensures a high accuracy and information content of the obtained data, which often exceeds that obtained using more traditional methods. The significant advantages of UAVs compared to manned aircraft are their small size, low noise level, and safety for the researcher. A promising direction associated with the widespread use of UAVs in scientific research is the use of automated methods for processing and analyzing images. The development of computer vision and deep learning algorithms provides opportunities for efficient work with large volumes of photo and video material. The use of drones is limited by the relatively short duration of continuous operation and the demands on external conditions for flight, as well as the impact on animal behavior. A significant limitation in the use of UAVs is their impact on animals. Many mammal species exhibit anxiety and marked avoidance when approached by a drone. Approach by a UAV may also affect mammals in less obvious ways, such as by altering the time budget spent on various activities or by inducing physiological stress responses. Researchers need to minimize the duration and intensity of exposure, particularly noise from UAVs, and to take into account the species characteristics of the animals and their environment. Before starting work, it is necessary to determine the optimal flight altitude at which a reaction by animals is absent or minimal. The experience of using UAVs for mammal research in Russia is quite diverse and reflects global trends towards the increasing introduction of this technology into zoological research.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any human or animal studies meeting the criteria of Directive 2010/63/EU.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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