drones

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Review

Impact of Drone Disturbances on Wildlife: A Review †

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Abstract: Drones are becoming increasingly valuable tools in wildlife studies due to their ability to access remote areas and offer high-resolution information with minimal human interference. Their application is, however, causing concern regarding wildlife disturbance. This review synthesizes the existing literature on how animals within terrestrial, aerial, and aquatic environments are impacted by drone disturbance in relation to operational variables, sensory stimulation, species-specific sensitivity, and physiological and behavioral responses. We found that drone altitude, speed, approach distance, and noise levels significantly influence wildlife responses, with some species exhibiting increased vigilance, flight responses, or physiological stress. Environmental context and visual cues are also involved in species detection of drones and disturbance thresholds. Although the short-term response to behavior change has been well documented, long-term consequences of repeated drone exposure remain poorly known. This paper identifies the necessity for continued research into drone–wildlife interactions, with an emphasis on the requirement to minimize disturbance by means of improved flight parameters and technology.

Keywords: drones; wildlife disturbance; animal behavior; conservation; ethical drone use

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1. Introduction

Unmanned aerial vehicles (UAVs, drones) are becoming increasingly popular for wildlife research purposes, offering a new set of opportunities for observation and data collection. Recent drone applications include an extensive range of activities, from collecting biological samples [1], tracking morphometric characteristics [2], and collecting behavioral data [3,4] to conducting census surveys [5], anti-poaching surveillance [6], and mapping the habitat use of species [7]. The technology has allowed scientists to access remote sites [8], investigate fine-scale wildlife movement patterns, and use automated image analysis methods for cost-effective species detection [9].

Despite these promising advancements and diverse applications, the growing integration of drones into wildlife studies has drawn concerns regarding their potential misuse and

escalating anthropogenic pressure. While drones have, in certain cases, been less obtrusive than previous methods of data collection [10], studies have demonstrated that drones have the ability to alter animal behavior, trigger physiological stress, and, in certain cases, lead to habitat displacement. Media have brought to light instances of wildlife harassment that have been captured in social media videos, which have increased public alarm [11]. The portrayal of drones as sources of disturbance in natural habitats has led to discussions about the need for a comprehensive evaluation of these concerns [11]. In light of these issues, some countries have banned the use of drones in protected regions, while stressing the need to respond to these emerging anthropogenic pressures [12].

The literature suggests that noise from drones is a critical factor influencing terrestrial, bird, and aquatic animal behavior during drone encounters [13–16]. Visual information, i.e., the visibility and proximity of the drone, may also contribute to behavior change, particularly for birds, since they can perceive drones as a potential threat or predator [17–20]. The auditory system in mammals, which is often very sensitive, triggers rapid neural responses, leading to swift fight-or-flight behavior [21]. The degree of disturbance depends on the strength and context of the stimulus, including flight altitude, speed, proximity of approach, and environmental conditions such as habitat type and time of day. Different species exhibit varying sensitivities, with some showing habituation to stimuli over time while others display heightened avoidance behaviors or sensitization. Although studies have explored specific drone stimuli such as sound [22] and visual cues [23], the individual impacts of these signals on animal behavior remain poorly understood. To overcome this gap and raise awareness about the impact of drone disruptions on wildlife, the article offers an in-depth review of existing research on wildlife ending in recommendations for drone operators, engineers, and policymakers.

This paper emphasizes the dual perspective of animal welfare and the potential behavioral alteration caused by drone disturbances and advocates a comprehensive consideration of drone disturbance effect and ethical issues in wildlife research. This paper also raises a fundamental question to the engineering community: Can we design drones that minimize disturbance to animals while still complying with legislation requiring transparent drone operations?

Our review builds on earlier work that offered a preliminary analysis of drone-induced wildlife disturbances through focused case studies [24], expanding it to address species-specific responses, drone flight paths, and environmental factors. This provides a framework for guidelines and recommendations on the technological development of the ethical use of drones in wildlife research that minimizes harm to the animals under study. An understanding of such interactions is crucial in balancing wildlife protection goals with the effective application of drones and ensuring that technological advancements align with wildlife protection principles. This paper contributes to the ongoing discourse on responsible drone applications, focusing on the importance of continuous innovation in drone design and use for protecting ecological integrity.

2. Material and Methods

The literature on the use of UAVs for wildlife monitoring and research, their interactions, and associated impacts was comprehensively reviewed up to 31 December 2023. Supplementing this review, we conducted a targeted search for scientific literature that explicitly addresses drone noise and its impact on land animals. Using the keywords ‘drone’, ‘unmanned aerial vehicle’, ‘unmanned aerial system’, ‘remotely-piloted aircraft system’, ‘unmanned aircraft’, ‘UAV’, ‘UAS’, and ‘RPAS’ together with the terms ‘wildlife’, ‘disturbance’, ‘animals’, ‘birds’, ‘marine’, ‘aquatic’, ‘reptiles’, ‘terrestrial’, and ‘megafauna’, we identified relevant publications using Google Scholar search and Web of Science. An ini-

tial search returned the absence of published work considering the impact of drone noise in terrestrial ecosystems specifically. Accordingly, we expanded our literature search to include drone impact studies on both aerial and aquatic habitats. To ensure a comprehensive review, publications were selected from peer-reviewed journal articles, university theses (Master's theses included), conference papers, and project reports. We also traced relevant publications referred to in other studies. This yielded a total of 92 studies.

This search was further complemented by the drone working group at The Wildlife Society, which identified 1572 peer-reviewed articles on wildlife and drones as of 15 December 2024. We reviewed the references within this collection to extract research specifically addressing drone disturbances on wildlife, focusing on drone operational factors, sensory stimuli, species- and habitat-specific sensitivities, and physiological and behavioral responses. Our integrated approach provides a comprehensive understanding of drone utilization in wildlife studies, and specific insights into the effect of drone noise on animals (see Figure 1 for the summary).

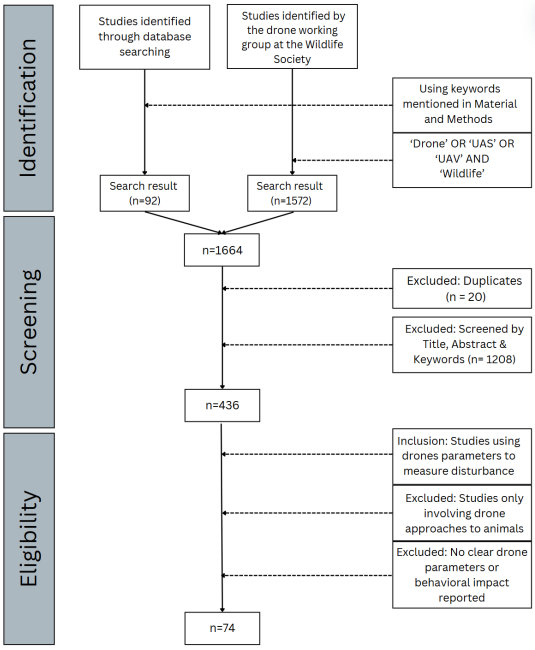

Figure 1. PRISMA-based flow diagram showing inclusion and exclusion steps for studies on drone disturbance in wildlife.

This review first considers drone–wildlife interaction, where the principal factors are flight altitude, speed, proximity, and noise. It then examines species-specific behavior responses to these parameters, across terrestrial, aerial, and aquatic environments. Following this, a framework for recommended drone operation parameters is developed, providing guidelines to minimize wildlife disturbance against the complexity of environmental stimuli and the long-term impact of repeated exposure to drones. Ethical considerations are integrated throughout our analysis, emphasizing the need for responsible drone use in wildlife research. The paper concludes by proposing future directions for technological advancements and development of species-specific mitigation strategies. Finally, the necessity for international collaboration in setting standards for the ethical utilization of drones is underscored to facilitate the responsible integration of UAVs into ecological research.

3. Drones and Wildlife

The earliest observations of aerial vehicle-induced disturbance behaviors were noted in studies that primarily focused on using aircraft to estimate population numbers [25].

Once researchers discovered how the accuracy of the census could be affected by the aversive reaction of the animals, the issue gained more direct and focused attention [26,27]. Various factors influence the effect of drones on wildlife, from operational characteristics, to environmental and habitat conditions, to an animal's biological state.

3.1. Operational Factors Influencing Wildlife Responses

The flight characteristics of drones dictate the strength and modality of the experienced sensory stimulus. Specifically, research suggests approach distance and altitude to be a primary influencing factor in inciting wildlife disturbance. For example, stationary birds generally exhibited minimal reaction to drones that maintained a distance of more than 40 m during take-off [17]. In another study on gentoo (*Pygoscelis papua*) and Adélie (*Pygoscelis adeliae*) penguins, researchers found that penguins on Ardley Island exhibited greater behavioral changes to drones flown at lower altitudes. Adélie penguins responded at 50 m, while gentoo penguins reacted at 30 m. Increased vigilance reactions were most pronounced at altitudes of 10–20 m [20]. A study on 11 seabird species on the Crozet Island found that reactions varied by species and altitude: at 50 m, only one species showed a response, while at 10 m, most species exhibited significant stress behaviors [28]. Both terrestrial and marine mammalian species from a range of taxonomic groups have demonstrated similar disturbance responses to drones, suggesting some universality of effect. A study on grey kangaroos (*Macropus giganteus*) in urban environments found that while drones often trigger vigilance, kangaroos rarely flee unless the drone flies at an altitude of 30 m or lower [29]. Similarly, in African reserves, elephants and giraffes have been documented to show increased vigilance when drones approach at distances of 50 m and 80 m AGL, respectively [30]. In a study on bottlenose dolphins (*Tursiops* ssp.), researchers indicated that dolphin behavior was significantly influenced by drone altitude [14]. In a study involving waterfowl, researchers found that waterfowl on land are more vigilant when approached by drones, with greater disturbance observed at lower altitudes and closer take-off distances [19]. However, the species- or taxon-specific strength of response is often difficult to disentangle from the types of drones the wildlife are exposed to, given high variability across studies in both drone protocol and environment.

Approach angles and speeds also influence wildlife behavior. We found that a direct approach from above can result in higher behavioral responses due to the fact that animals cannot look directly about them and hearing the drone noise approaching them induces more stress on the wildlife. One study reported that drones can approach waterfowl within close proximity (e.g., 4 m) without causing significant disturbance, provided they avoid direct approaches from above [18]. Also, maintaining specific airspeeds (e.g., 20–25 km/h) has been noted to minimize disturbance, allowing drones to pass by wildlife before they become fully aware of their presence [31]. It can be hypothesized that high drone speed can leave the animal with no time to identify whether the drone is a threat or not, which leads to sudden responses from the wildlife.

A few more studies reported in Table 1 also support our findings that flight characteristics significantly affect animals response. Thus, the interaction of altitude, approach distance, take-off distance, airspeed, proximity, and approach angle can contribute towards the disturbance of wildlife across various habitats. The frequency with which these flight characteristics are highlighted underscores their importance in assessing the impact of drone operations on animals. Despite the observed species-specific variability, based on these studies, we recommend maintaining a higher altitude to reduce stress in wildlife, with slower speeds and oblique angles.

Table 1. Wildlife responses to drone flights across various species, highlighting the impact of UAV type, flight distance, and study context on behavioral reactions.

Study	Species Studied	Drone Used	Study Context	UAV Flight Altitude	Observed Impact	Recommendations
Assessing the Disturbance Potential of Small Unoccupied Aircraft Systems (UAS) on Gray Seals at breeding colonies in Nova Scotia, Canada (2018) [32]	Gray seals (*Halichoerus grypus*)	Fixed-wing UAS (eBee)	To assess the disturbance of UAS during population surveys	75–85 m	No significant changes in seal behavior (counts, posture, or movements)	Lower acoustics at higher altitudes found suitable for minimal invasive surveys.
First Guidelines and Suggested Best Protocol for Surveying African Elephants using a drone (2021) [33]	African elephants (*Loxodonta africana*)	DJI Mavic Pro Platinum	Investigating behavioral responses to drone speed, angle of approach, and initial altitude	Combination of flights: 35 m, 50 m, and 100 m with 2 m/s, 4 m/s, and 6 m/s, and approach angle of 45° and 90°	90° approach angle and higher speed reported to influence elephant behavior	Higher speed and high approach angles should be avoided to induce less stress on animals.
Przewalski's Horses Responses to Unmanned Aerial Vehicles Flights under Semireserve Conditions: Conservation Implication (2021) [34]	Przewalski's horses (*Equus ferus przewalskii*)	DJI Mavic 2 Zoom	Behavioral responses of Przewalski's horses to different UAV flight altitudes	1 m to 52 m	Alert and run-away responses varied by age and gender	Optimizing flights according to the biological state of the animal to minimize disturbance.
Dolphin Behavioral Responses to Uncrewed Aerial Systems as a Function of Exposure, Height, and Type (2023) [35]	Bottlenose dolphins (*Tursiops truncatus*)	DJI Mini 2, DJI Mavic 2 Enterprise, DJI Inspire 2, DJI Mini 3 Pro, DJI Avata, SplashDrone 4, PHASM fixed-wing UAS	Behavioral responses of bottlenose dolphins to different UAS types and heights	Hovering at 300 ft and descending to 20 ft (varied by UAS)	Larger, noisier UAS induced higher responses	Avoid lower drone flight altitudes
Fly with Care: Belugas Show Evasive Responses to Low Altitude Drone Flights (2023) [36]	Belugas (*Delphinapterus leucas*)	DJI Phantom 4, Phantom 4 Pro	Impact of drones on endangered St. Lawrence belugas	16.9 m to 124.9 m	Evasive reactions occurred at low-altitude flights. Larger groups were more likely to show avoidance responses.	Recommended flight altitude: >30 m. Group size also influences the increased alertness at lower altitudes.
Impacts of Drone Flight Altitude on Marsh Bird Behaviors and Species Identification of Marsh Birds in Florida (2023) [37]	Marsh birds, including passerines, wading birds, and waterfowl	DJI Mavic 2 Zoom	Evaluate the effects of drone altitude on marsh bird behavior	12 m, 30 m, 61 m, and 91 m	Minimal behavioral reactions at 12 m and 30 m	Lower altitudes can be opted only if animals shows no disturbance.
How low can you go? Exploring impact of drones on haul out behaviour of harbour—and grey seals (2024) [38]	Harbor seals (*Phoca vitulina*), Grey seals (*Halichoerus grypus*)	DJI Phantom 4 Pro, Autel EVO II RTK	Impact of varying drone flight altitudes and approaches on harbor and grey seal behavior	70 m to 10 m, descending by 5–10 m intervals	Increased vigilance and displacement at altitudes < 30 m	Direct overheads path should be avoided with lower speeds to minimize disturbance.

3.2. Sensory Stimuli: Noise and Visual Impact

As noted above, research has shown varying responses to drones among species, with differences in whether species are primarily responding to visual or acoustic stimuli

(Table 2). For example, bottlenose dolphins (*Tursiops truncatus*), known for their clear visual acuity in both water and air [39], may rely on visual cues, while manatees (*Trichechus manatus latirostris*), with poorer visual acuity [40], might respond more to the noise produced by drones. Observations of manatees (*Trichechus manatus manatus*) exhibiting sudden escape behaviors when approached by drones suggest that noise could play a significant role in their detection [41]. Similarly, elephants have been widely observed to move away from drones due to their bee-swarm-like sounds [15]. Asian elephants (*Elephas maximus*) were shown to become disturbed at an average altitude of 109 m AGL. The study found that this heightened sensitivity is due to their ability to detect and respond to low-frequency sounds, which drones can produce [13]. These findings corroborate the observations reported by Moss et al., 2011 [42], which emphasize the reliance of African elephants on their auditory abilities for environmental interaction and communication with conspecifics. Similarly, a study that assessed the behavioral responses of southern white rhinos (*Ceratotherium simum*) to drone flights found that animals could perceive the drone up to 100 m AGL and that acoustic output alone was enough to initiate a reaction [43]. One of the most comprehensive study to date [44] contrasted sound profiles of seven drone systems at various altitudes with the audiograms from 20 mammal species.This method provides valuable guidelines for drone use in wildlife research and conservation, with potential applications for other species and drone systems. Among species without audiograms, the giant anteater (*Myrmecophaga tridactyla*)—an endangered species and the largest in the Pilosa order—was exposed to drone studies for the first time [45]. Due to its limited auditory and visual capabilities, the giant anteater showed a high tolerance for sound pressure before exhibiting any behavioral changes, as predicted [45]. Prior knowledge of species hearing thresholds may occlude the need to exhaustively test drones across different species types also because there are similar experiences shared across species with certain habits. More research is needed to learn about the effects of drone size and noise traits on wildlife, since responses might also be determined by species-specific hearing sensitivity differences.

Research also suggests that drones can disturb animals, particularly through visual cues when noise is masked by environmental sounds. One hypothesis is that the visual impact of drones may mimic the shape or movement of predatory birds, triggering instinctive defensive or escape behaviors, particularly among species sensitive to aerial predators [46–48]. This is supported by studies that have shown shape and wing profile of certain drones have influenced the reactions of waterfowl, with profiles resembling raptors causing the most disturbance to wildlife [49] and that disturbance tends to occur more frequently during drone banking maneuvers, take-off, or landing, especially when these actions happen over or near a flock, suggesting that birds may interpret these movements as the swooping of a predatory bird [49,50]. For example, lekking prairie chickens (*Tympanuchus cupido*) display heightened sensitivity to drone overflight, which may be attributed to the vulnerability of displaying birds to potential attacks by hawks [51,52]. Beyond evasive behaviors, some bird species were documented engaging in harassment, mobbing, or direct attacks on drones mid-flight [53]. A visual representation in Figure 2 depicts a raven attacking a delivery drone. Further research into how the drone type and its visual characteristics affect not only birds but other taxa is warranted, particularly where species may be at risk of aerial predation (for example, primates, rodents, and even fish) which remains an under researched area.

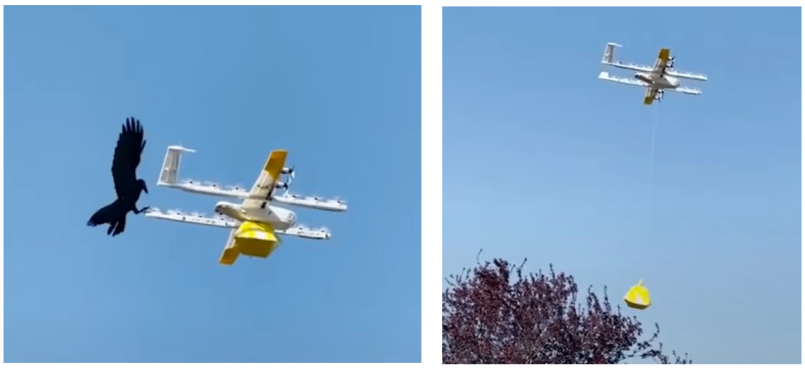

Figure 2. Raven attacks drone delivering coffee in Australia [54].

Table 2. Wildlife responses to drone noise and visual stimuli across species, UAV types, and flight conditions.

Study	Species Studied	Drone Used	Study Context	UAV Flight Altitude	Observed Impact	Recommendations
Fleeing by Whimbrel in Response to a Recreational Drone (2016) [55]	Whimbrel (*Numenius phaeopus*)	Recreational drone (Phantom type)	Observing the response of Whimbrel to a recreational drone	Hovered at 5 m and 20 m altitudes	Whimbrels exhibited strong "fleeing" responses	Avoiding low-altitude flights near sensitive bird species.
Using Two Drones to Monitor Visual and Acoustic Behaviour of Gray Whales (*Eschrichtius robustus*) in Baja California, Mexico (2020) [56]	Gray whales (*Eschrichtius robustus*)	SwellPro SplashDrone 3+ (acoustic) and DJI Phantom 4 (visual)	Testing dual-drone system for simultaneous visual and acoustic monitoring of gray whale behavior	30 m for visual drone; acoustic drone within 50 m	Minimal disturbance observed.	More research is needed on dual-drone monitoring with varying altitudes.
Measuring Disturbance at Swift Breeding Colonies Due to the Visual Aspects of a Drone (2021) [23]	Great dusky swift (*Cypseloides senex*), White-collared swift (*Streptoprocne zonaris*)	DJI Mavic Pro	Assessing visual drone disturbance on great dusky swift	25 m to 64 m	At <40 m, disturbance increased to >60%, leading to temporary colony abandonment.	Recommended flight altitude: >50 m to minimize disturbance.
Determination of Optimal Flight Altitude to Minimise Acoustic Drone Disturbance to Wildlife Using Species Audiograms (2021) [44]	Various mammals (20 species)	DJI Inspire 2, Phantom 4, Mavic 2, Mavic Pro, Mavic Pro Platinum, Mavic Mini, Spark	Determining the minimum flight altitude to minimizes UAV noise disturbance	5 m to 120 m	The optimal altitude varies by species and drone model	Recommended altitudes of 35 m to 120 m depending on species.
Behavioral Responses of a Nocturnal Burrowing Marsupial (*Lasiorhinus latifrons*) to Drone Flight (2021) [57]	Southern Hairy-Nosed Wombat (*Lasiorhinus latifrons*)	DJI Phantom 4 Pro	Assessing the behavioral responses of southern hairy-nosed wombats during day and night	100 m, 60 m, 30 m	Night flights triggered stronger retreat responses	Conduct flights outside sensitive hours to reduce disturbance.
Drone noise differs by flight maneuver and model: implications for animal surveys (2024) [58]	Not species-specific	DJI Matrice 300, Matrice 200, Phantom 3, Autel Evo II	Evaluating noise emission differences by drone model, flight maneuver, and altitude	15 m to 120 m	Flyover and turning maneuvers at higher altitudes generated minimal noise	Avoid repetitive sessions and minimize prolonged hovering.

3.3. Species- and Habitat-Specific Sensitivities

Animal behavior depends on species-specific traits and environmental conditions. Accordingly, much of the literature on the non-intrusive monitoring of animals focuses on tailoring drone use guidelines to species-specific responses, often suggesting minimum altitudes of flight for observational research [30,41]. One of these studies on seven African herbivore species reported negative responses to drones, which were flown at different altitudes, as shown in Figure 3. The vigilance threshold differed between species, with some animals avoiding drones at around 50–60 m, while others reacted at 15–30 m AGL [30]. Interestingly, with plains zebras, no avoidance response was observed at about 80 m AGL, but there was alertness at 100 m [30]. Such counterintuitive behavior may be caused by factors such as the path of flight of the drone; atmospheric conditions such as wind amplifying noise at higher altitudes; or line-of-sight perception by the zebras. These results highlight the complexity of species-specific sensitivities and the need for further research to more fully understand the relationship between drone flight parameter and wildlife responses before a more general rule can be applied.

Responses to drones are affected by both abiotic and biotic factors, which can vary not only annually and seasonally but also throughout the day, influenced by specific habitat and anthropogenic effects. For example, environmental changes such as temperature gradients and varying sound propagation speeds—both affected by sunlight—can significantly alter the response to drones. Drone-generated noise can also be amplified or diminished based on weather conditions such as wind speed, wind direction, and humidity. Humid air, which transmits sound waves more efficiently [59], can enhance the extent to which drone noise affects wildlife. Furthermore, in varying wind conditions, animals react differently to drone noise, thus influencing their respective behavioral responses. These dynamic atmospheric conditions and cyclical changes in light level across a day are such factors that can strongly affect the transmission and hence detectability of both visual and auditory stimuli generated by drone flights. This—coupled with circadian rhythmicity in animal behavior and physiology, differing environmental conditions throughout the day, and advancements in drone technology—calls for a deeper investigation into how drone impacts on wildlife vary over a 24 hour cycle and whether they remain consistent across species [57].

Exposure levels to human activity can also be a predictor of wildlife reactions. Animals in remote, undisturbed habitats often have more intense reactions to drones compared to those in human-altered environments, where habituation to human presence may exist [13]. Habituation is the process where animals gradually reduce their responses to repeated or benign stimuli, while sensitization might occur if the stimulus is perceived as harmful or intrusive. For example, wildlife in heavily visited safari parks may be less alert than those in remote reserves, where drone noise could be identified as a novel disturbance. It is important to note that not only exposure history to drones can influence reactions, but other industrial, urban, or vehicle-related noise may also lead to lower behavioral responses to drones, even from wildlife that have not been exposed to drones previously.

Beyond environmental factors, ecological and behavioral contexts also shape how animals perceive drones. Behavioral patterns can help to minimize competition and risk of predation [60]. For instance, prey species often occupy alternative habitats or are active at different hours of the day than their predators according to their vulnerability to predators within an environment, hiding or taking evasive action to reduce their risk [61]. In areas with high predator densities, prey species are more vigilant, and this increases their sensitivity to novel disturbances such as drones [62]. Heightened vigilance causes prey species to react to drones as potential predators, which elicits a flight or stress response. Even without any immediate response, the energy and time spent on vigilance can indirectly

reduce fitness because it takes away from the energy available for typical activities such as foraging and parental care. For instance, herbivore groups were observed changing their activity from foraging to vigilance and locomotion when they sensed drone scanning flights [63]. Responses to drone disturbance may also depend on the nature of the landscape, for instance, visual openness (Table 3).

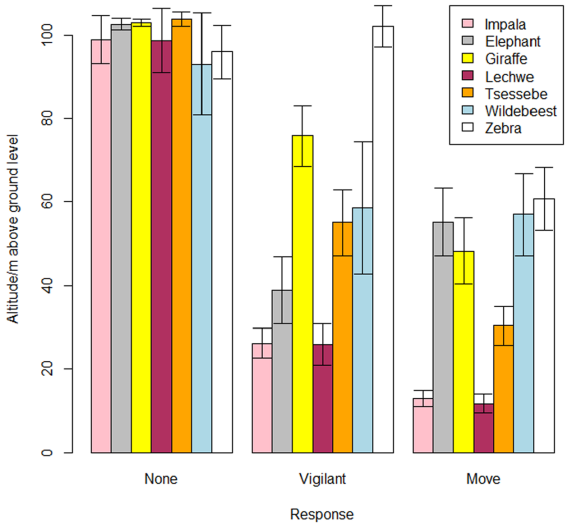

Figure 3. Behavioral responses of seven African herbivore species to drone approaches at varying altitudes [30]. Drone altitude is presented on the *x*-axis in m (m), and the percent (%) of animals exhibiting a behavioral response (e.g., alertness, flight, or no response) is presented on the *y*-axis. Responses are categorized by species and plotted to determine differences in sensitivity among altitude levels.

For instance, in a review of existing studies coupled with public YouTube recordings of animal behavior (Figure 4), ref. [11] documented how species inhabiting aquatic habitats had a lower likelihood of exhibiting behavioral change than those found in terrestrial and aerial habitats. This reduced sensitivity likely relates to a reduction in signal strength beneath the water [64–66] and the situation that that most of the assessed species were not at risk of predation or other threats from above and have therefore not developed awareness and defensive behaviors to such stimuli even when they are novel. Upon comparing recorded drone noise levels with the established hearing thresholds of dolphins and whales, it became evident that, for the majority of these marine mammals, drones operate beneath their auditory thresholds [67]. An investigation centered on southern right whale (*Eubalaena australis*) mother–calf pairs in Australia utilized drone tracking and acoustic tag data and found no observable behavioral reactions to close drone approaches [68]. Other studies, while anecdotal, have reported similar findings for various baleen whale species, such as gray whales (*Eschrichtius robustus*) [69], humpback whales (*Megaptera novaeangliae*) [70], bowhead whales (*Balaena mysticetus*) [71], and blue whales (*Balaenoptera musculus*) [72]. In the case of toothed whales (*Tursiops truncatu*), a study [73] disrupts this assumption, showing heightened signs of disturbance, including increased reorientation and tail slapping in bottlenose dolphins when a drone operated at an altitude of 10 m. Surprisingly, such effects dissipate at higher altitudes of 25 m to 40 m, challenging a reevaluation of the presumed harmlessness of drones near cetaceans. Another study [41] also showcased the behavioral responses of bottlenose dolphins to drones, as shown in Figure 5. In the case of terrestrial mammals, drone exposure triggers flush responses, hypothesized to be an avoidance reaction to encounters with unfamiliar objects. However, a limitation with this and other studies is that many drone-based observations are limited to mammalian

megafauna [74] and their use in recreational filming, with limited study of the reactions of other taxonomic groups.

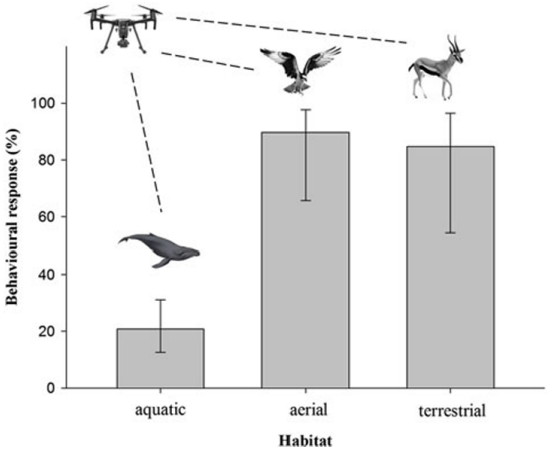

Figure 4. Variation in wildlife behavioral responses to aerial vehicles according to their primary habitat [11]. The *X*-axis is habitat categories (e.g., aquatic, aerial, and terrestrial), and the *y*-axis is percentage of studied species showing drone-induced behavioral responses. Reprinted/adapted with permission from [11]. 29 November 2024, Saadia Afridi.

Table 3. Wildlife responses to drone flights in different habitats, highlighting species-specific and environmental sensitivities.

Study	Species Studied	Drone Used	Study Context	UAV Flight Altitude	Observed Impact	Recommendations
Terrestrial Mammalian Wildlife Responses to Unmanned Aerial Systems Approaches (2019) [30]	Elephants, Giraffes, Wildebeest, Zebras, Impala, Lechwe, Tsessebe	DJI Phantom 3, DJI Inspire 1	Assessing vertical and horizontal UAS approaches	10 m to 100 m	Horizontal approaches triggered fewer reactions than vertical ones	Recommended minimum altitude of 60 m and horizontal distance of 100 m.
Responses of Bottlenose Dolphins (*Tursiops* spp.) to Small Drones (2020) [14]	Bottlenose dolphins (*Tursiops* spp.)	DJI Phantom 4	Examining drone altitudes and observation durations influence	5 m to 60 m	Groups exhibited more reactions at <30 m altitude. Longer hovering times increased the probability of behavioral responses	Recommended flight altitude: ≥30 m to minimize disturbance.
Ungulate responses and habituation to unmanned aerial vehicles in Africa's savanna (2023) [75]	Oryx, Kudu, Springbok, Giraffe, Eland, Hartebeest, Plains Zebra, Impala	DJI Phantom 3, DJI Mavic Pro, Custom X8 (Octocopter), Sky Eye	Assessing the behavioral responses of ungulates to UAV flights	15 m to 55 m	Species-specific responses varied by altitude and UAV type	Opting for species-specific flight altitudes to reduce disturbance impact.
Estuary Stingray (*Dasyatis fluviorum*) Behavior Does Not Change in Response to Drone Altitude (2023) [76]	Estuary stingray (*Dasyatis fluviorum*)	DJI Mavic Platinum Pro	Assessing if drone altitude influences the behavior of estuary stingrays	5 m to 30 m, reducing by 5 m intervals	No significant changes in swimming, foraging, or resting behavior	Further research required into physiological and long-term impact of drone disturbances.
Assessing the Behavioral Responses of Small Cetaceans to Unmanned Aerial Vehicles (2021) [77]	Common dolphins (*Delphinus delphis*), Bottlenose dolphins (*Tursiops truncatus*)	DJI Phantom 2	Evaluating the behavioral responses to drones at different altitudes	5 m to 70 m (descending in 5 m intervals)	No significant responses in diving or swimming speed for either species	Observing animals' reaction and adjusting flight according is essential for minimizing disturbance.
Sociability Strongly Affects the Behavioral Responses of Wild Guanacos to Drones (2021) [78]	Guanacos (*Lama guanicoe*)	DJI Phantom 4 Advanced	Examining group size, social composition, and flight characteristics on guanaco	60 m and 180 m with low (2–4 m/s) and high (8–10 m/s) speed	Groups exhibited greater reaction probabilities. Low altitudes (<60 m) increased reactions	To consider collective responses versus those of lone individuals when utilizing drones in ecological studies.

Purely observational studies often lack consideration of physiological and metabolic reactions in animals which can show cryptic or counter-intuitive effects on the behaviors witnessed. For example, hibernating black bears (*Ursus americanus*) show (Figure 6) elevated heart rates to overhead drones [79]. Meanwhile, female American black bear with at least two cubs exhibited fastest movement, relocating 576.3 m away within 40 min of drone exposure. Southern white rhino mothers with calves showed a heightened response to drone flights compared to solitary males or groups of sub-adult individuals, suggesting they may perceive risk differently to other social groupings due to their calf's increased susceptibility to predation [43].

The biological state of an animal refers to its physiological condition and the activities it is engaged in at a particular time, such as breeding, nesting, molting, or foraging. These states can influence how an animal perceives and reacts to external stimuli, including the presence of drones. For example, animals in vulnerable life stages, such as breeding or parental nest defense, will most likely exhibit heightened sensitivity to disturbances. Harbor seals (*Phoca vitulina*) respond to drones flown at an 80 m threshold distance for the pre-breeding season but show heightened agitation at 150 m for the molting season [80]. Studies also show that nesting birds, such as Adélie and gentoo penguins, respond differently to drones [20], and thus the incorporation of biological state in the design of drone missions is critical [17,71,81]. Disturbances during sensitive periods, such as breeding seasons, can lead to severe behavioral changes, including nest abandonment or increased energy expenditure [82], potentially affecting reproductive success [66]. We recommend to maintain greater distances from animals during these critical life stages to minimize behavioral disruptions.

Similarly, nesting birds may engage in nest-guarding behaviors to prevent the intrusion of objects into their territory, and drones may violate these boundaries, causing defensive or flight responses. Moreover, for these birds, the combined visual and auditory disturbances from drones can lead to increased vigilance, agonistic behavior, standing or walking away from nests, and escape behaviors [83,84]. Supporting this hypothesis, a study on great dusky (*Cypseloides senex*) and white-collared (*Streptoprocne zonaris*) swifts found that drones flying within 40 m caused significant disturbances, leading over 60% of birds to temporarily abandon their breeding sites [23]. Despite the likelihood of species-specific differences, given the risk of extreme negative reactions, it is recommended that drones maintain a general distance of over 50 m above birds during breeding season, and that recreational flights be kept at least 100 m away from nesting areas.

Figure 5. Instances of bottlenose dolphin reaction to the presence of drone comprised (**A**) side-roll, (**B**) belly-up, (**C**) circular swim (left), (**D**) spin-and-orient, (**E**) side-roll (open-mouth), and (**F**) breach (inverted) [41].

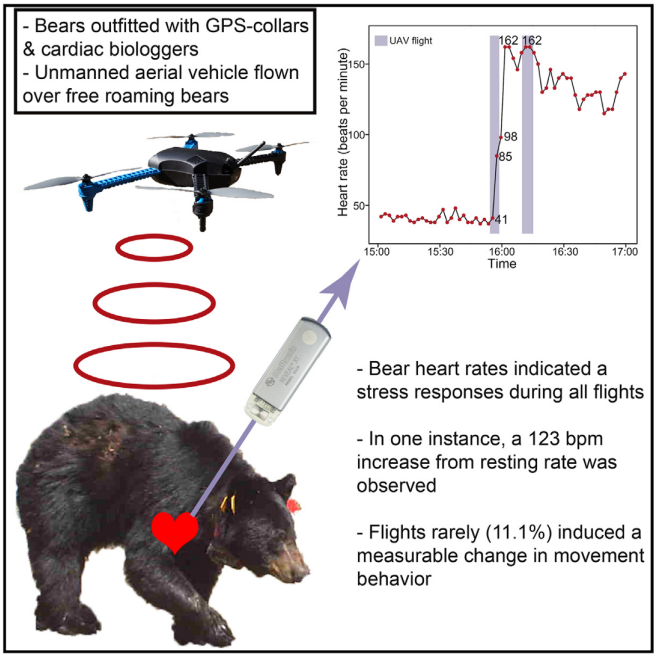

Figure 6. Bears showed elevated heart rates in response to drone flights, with minimal behavioral reactions. Reprinted/adapted with permission from [79]. 29 November 2024, Saadia Afridi.

Variation in biological state can have a significant impact on responses, particularly when there is an energy deficit. Starving or energy-starved animals can exhibit riskier behavior or tolerate more disturbance since they prioritize food acquisition over threat avoidance [85,86]. This threat-sensitive foraging can explain variation in wildlife responses to drones across seasons and environmental conditions [87].

Size demographic of social groupings can also affect tolerance of risk and hence be a further factor in explaining context-specific behavior differences in response to drones [14]. Group size has been reported to modify animals' responses toward drones, with larger groups exhibiting increased avoidance. For instance, beluga whales (*Delphinapterus leucas*) in larger groups were observed to exhibit stronger avoidance responses and tended to execute sudden dives in low-altitude flights, particularly at altitudes below 23 m [36]. Groups with more individuals had a higher chance of sudden dives (shown in Figure 7), particularly when a drone initially approached the group showing a need to maintain a reduced drone distance in these contexts.

Figure 7. Beluga exhibit avoidance reactions to drones when in large groups [88].

In summary, it is crucial that further research is conducted to investigate the complex interplay that exists between specific sensitivities and the different biological states of an animal, in order to accurately interpret drone-induced effects on wildlife behavior (Table 4). This is most true of drone exposure during critical periods such as breeding or seasonal energy deficits, which has the greatest potential to affect individual fitness or even introduce population-level effects when drones are flown above breeding colonies or vulnerable juvenile animals [89]. More research is needed to understand how environmental factors can amplify disturbances to the acoustic or visual cues needed for communication, navigation, or predator detection.

Table 4. Physiological and behavioral responses of wildlife to drone flights across different species.

Study	Species Studied	Drone Used	Study Context	UAV Flight Altitude	Observed Impact	Recommendations
Bears Show a Physiological but Limited Behavioral Response to Unmanned Aerial Vehicles (2015) [79]	American black bear (*Ursus americanus*)	3D Robotics Quadcopter	Assessing physiological and behavioral responses to drone flights	20 m to 43 m	No behavioral responses (movement or avoidance) but increased stress (heart rate of 123 bpm)	Developing frameworks that consider species' vulnerability and additional stress.
Fright or Flight? Behavioral Responses of Kangaroos to Drone-Based Monitoring (2019) [29]	Eastern grey kangaroo (*Macropus giganteus*)	DJI Phantom 3 Advanced	Assessing vigilance behavior to drone altitude and flight characteristics	30 m to 120 m	Flight responses most frequent at 30 m altitude	Minimum flight altitude of 60 m is recommended to minimize disturbance.
Koalas Showed Limited Behavioral Response and No Physiological Response to Drones (2023) [90]	Koalas (*Phascolarctos cinereus*)	DJI Mavic 2 Pro	Assessing behavioral and physiological to drones	15 m above the enclosure	Short-term increase in vigilance but no significant change in heart rate or breathing rate	Further research required on the behavioral and physiological responses.
Evaluating Behavioral Responses of Nesting Lesser Snow Geese to Unmanned Aircraft Surveys (2018) [91]	Lesser snow geese (*Anser caerulescens caerulescens*)	Fixed-wing Trimble UX5	Measuring behavioral responses of nesting snow geese	75 m, 100 m, and 120 m above ground	Increased vigilance (head cocking and scanning) during flights	Closer proximity may be acceptable only if it ensures minimal stress to the species.
Will Drones Reduce Investigator Disturbance to Surface-Nesting Birds? (2017) [92]	Various surface-nesting seabirds (e.g., gulls, penguins)	DJI Phantom, Trimble UX5, other off-the-shelf drones	Assessing drone-based monitoring disturbance in surface-nesting seabirds	50 m to 120 m depending on species	Species-specific responses varied. Visual predator-like flight patterns (e.g., vertical approaches) increased reactions.	Avoiding direct overhead flight patterns.
Behavioral Responses of Geoffroy's Spider Monkeys to Drone Flights (2024) [93]	Geoffroy's spider monkeys (*Ateles geoffroyi*)	Mavic 2 Enterprise Advanced	Assessing drone flight influence on spider monkey	35 m, 50 m flight heights	Minimal changes observed in behaviors	More research is required to explore long-term behavioral impact and habituation to drones.

4. Best Practices and Recommendations

Based on the comprehensive review of the impacts of drone disturbances on wildlife in Section 3, we recommend the following best practices to inform drone-based wildlife research with minimal effect on animal behavior and habitat. The best practices are designed to reduce effects on animal behavior and habitats through standardizing key parameters, such as flight altitude, approach methods, environmental factors, and ethical considerations, establishing a comprehensive framework for responsible drone use.

4.1. Flight Parameters

Altitude is a primary factor that affects wildlife disturbance. There is evidence to suggest maintaining altitudes between 40–80 m reduces stress, particularly in large terrestrial mammals and bird species, as supported by findings in Section 3.1. In terrestrial wildlife, flying drones more than 35–80 m from the wildlife reduces the response in terms of vigilance or avoidance responses [29,30]. Breeding birds, especially during breeding periods, are very sensitive, and flights need to be at or higher than 80 m to avoid reproductive disturbance [19]. Marine mammals are less affected by flights at higher altitudes, but flights below 30 m can cause avoidance behavior and should be restricted to essential tasks [14].

Proximity to the animals also affects their responses significantly (see Table 1). For large mammals, an approach distance of 30–50 m minimizes avoidance behaviors, while birds benefit from a horizontal distance of 50–80 m, especially during nesting or breeding periods. Marine animals, too, require the same lateral distances of 40–60 m or more to minimize disturbance. Proximity at smaller distances can be accepted in cases where the animals exhibit neutral behaviors; however, starting observations at a distance and approaching in phases minimizes stress.

Drone speed and flight path also influence animal behavior. Speeds below 5 m/s are recommended, particularly in the vicinity of groups or juveniles, as low speeds minimize the potential for stress reactions [33]. Lateral or oblique movements by drones are preferable, as direct overhead paths may be imitated as predator movement, particularly in birds and small land animals, and hence best avoided [17,18].

4.2. Species-Specific and Contextual Sensitivity

Species-specific sensitivity to drones is influenced by species' auditory and visual thresholds as well as its biological states. For example, drone activity should be minimized near nesting, breeding, and post-breeding habitats during peak seasons, with altitude and distance varied to reduce disturbance, especially when parental care for juveniles may enhance sensitivity to disturbances in these vulnerable settings [17,66,71,81–83]. No-fly zones may be required in order to prevent interference with natural behaviors, which is a direct application of the findings in Section 3.3.

The ethical aspects of drone deployment are frequency and duration of use, and evidence indicates that repeated exposure to drones causes cumulative stress. Limiting drone activity to necessary observational time and the avoidance of repetitive or prolonged sessions is advised, particularly in high-sensitivity areas or situations involving vulnerable or threatened species [18]. Flight sessions of not more than 10–15 min are most typically recommended, as brief observation periods allow animals to return to their normal behavior sooner, which is critical to avoid prolonged effects of stress and to avoid disruption of foraging or breeding cycles [94].

Responsible drone use also must abide by rules that optimize wildlife welfare. Disturbance to some extent and any physical harm caused to animals are totally unacceptable regardless of the perceived conservation value or data collection aim of study. Ethical considerations must inform decision-making through the weighing of data collection need against that of minimizing disturbance. These protocols should consider species vulnerability, the nature of the ecological environment, and long-term study benefits [95,96]. For example, while drone usage in vulnerable habitats may pose immediate risks, it may also offer critical insights to inform habitat protection and restoration. Such decisions, nevertheless, need to place wildlife welfare as a primary consideration.

Species- and ecosystem-specific adaptation methods are needed for drone impact mitigation (see Section 3.3). These include flying at the optimal altitudes and ranges based on behavioral thresholds, using quieter drones with noise-reducing technology,

and using biomimetic designs which replicate natural forms such as birds or insects in order to minimize perceived threat. In forested habitats, for instance, dense vegetation can naturally dampen drone noise, whereas in open landscapes, operators need to employ flight parameters that do not alarm animals. Temporal adjustments—such as flying at times other than biological periods, and implementing adaptive management protocols that adjust drone flights based on real-time animal activity monitoring—are also key aspects of responsible drone use.

In addition, researchers can refer to existing ethical frameworks such as the 'Three Rs' principle (replacement, reduction, and refinement), commonly applied in animal studies, to minimize harm [97,98]. It assists in encouraging non-invasive techniques such as remote sensing and pre-recorded audio cues, emphasizing the minimization of stress while maximizing value from information collected for conservation.

4.3. Environmental and Temporal Considerations

Environmental conditions and the timing of drone operations significantly influence wildlife responses. Flights should be conducted outside peak activity periods, such as dawn and dusk, with consideration of animals' natural rhythms and avoiding disturbance at sensitive periods, a recommendation that is in line with research in Section 3.3 on environmental influences on wildlife reactions.

Weather also impacts drone noise propagation and animal responses. During windy or humid weather, sound travels further, amplifying disturbances for sound-sensitive species [59]. Drone flights would ideally be delayed during such conditions, especially where animals rely on acoustic cues for communication or predator evasion [61,62]. For studies conducted in open areas where there are no sound-dampening barriers, flight during still, clear weather also minimizes the likelihood of unintended noise amplification [57].

4.4. Behavioral Monitoring and Adaptive Drone Management

Real-time behavioral monitoring is a critical component of adaptive drone management for wildlife studies. Real-time video monitoring systems and telemetry data allow researchers to continuously assess wildlife reactions, with the ability to make adjustments in flights according to observed behavior [99]. For instance, increased vigilance or movement away from the drone should immediately result in an increase in altitude or a temporary suspension of flights. Such sensitivity helps to ensure that drone flights are maintained as minimally invasive as possible and helps preserve natural animal behavior.

A tiered descent protocol is also advised to prevent startling animals. Starting observation at a higher altitude (e.g., 80 m) and descending only as tolerated by animals is an effective approach. This approach is applicable whether animals show visible signs of stress or not [38]. In situations where no immediate stress responses are visible, continue to closely watch over the animals, maintaining conservative drone operation standards to prevent potential stress. Observing animals' reactions at each altitude and adjusting accordingly is the best way to minimize disturbances.

4.5. Data Collection and Standardized Reporting

Standardized logging of data is essential in promoting consistent practice across drone-based wildlife studies and facilitating possible comparisons among studies in the future [100]. Researchers are encouraged to develop detailed logs recording the flight parameters, environmental conditions, species observed, and specific behavioral responses at each phase of the drone operation. Time-stamped observations should also classify responses within existing behavior categories, e.g., vigilance or avoidance, to allow for accurate interpretations and facilitate cross-study analyses.

Supplementary telemetry and acoustic information support this standardization approach by providing objective measurement of drone noise levels at varying distances and altitudes. Telemetry information such as altitude, speed, and distance to animals allows researchers to correlate flight parameters with observed responses and modify protocols for target species [101]. For noise-sensitive habitats, the incorporation of acoustic measurement and drone audiograms gives the foundation for understanding the relationship between noise and species audiograms to ensure that drone noise is kept in moderation [58].

Finally, establishing a comprehensive shared repository for wildlife drone data would enable the sharing of data in a collaborative format, promoting consistency and efficacy of drone protocols in studies. The database would be a core platform for scientists, facilitating ease of cross-study comparisons and the development of universally effective ethical guidelines for drone applications in wildlife studies [102,103]. To avoid any potential data privacy and ethics issues, in particular relating to sensitive information for vulnerable species, the repository must ensure that proper access controls are applied such that only validated researchers have access to the data. If necessary, anonymization of data can be utilized for covering specific locations or identifiable animals to prevent them from possible harm. Further, all data storage and exchange must comply with the legal systems of the country where the data originated and should be handled under the authority of an ethics committee to ensure conservation and privacy standards on an international scale.

4.6. Regulatory Compliance

Ensuring regulatory compliance is a key component of conducting drone operations for wildlife conservation. National frameworks, systems, and procedures vary considerably; however, two primary categories of approval are generally required: (i) a drone operational permit issued by the national aviation authority, and (ii) conservation-specific approvals granted by the agencies or management bodies responsible for protected areas.

International guidelines are provided by bodies such as the International Civil Aviation Organization (ICAO), which offers recommendations at the international level but does not grant operational permits. Within the European Union, regulatory guidance is set by the European Union Aviation Safety Agency (EASA), which is implemented by member states through their respective aviation authorities. For instance, in France, drone operations are regulated by the Directorate General for Civil Aviation (DGAC); in Denmark, the Danish Transport Authority (Trafikstyrelsen) governs these activities, while in Germany, the Luftfahrt-Bundesamt (LBA)takes on this role.

Outside Europe, in the United States the Federal Aviation Administration (FAA) is the point of contact, in the United Kingdom the Civil Aviation Authority (UK CAA) oversees operations, and in Australia the Civil Aviation Safety Authority (CASA)governs drone activities. In Africa, each country maintains its own civil aviation authority. For instance, in Kenya the Kenyan Civil Aviation Authority (KCAA), and in South Africa the South African Civil Aviation Authority (SACAA) regulate drone operations.

In addition to obtaining aviation approval, drone operations over sensitive wildlife areas require obtaining conservation-specific approvals. These approvals ensure that the drone operations are conducted with minimal disturbance to wildlife and are managed by governmental agencies or local conservation bodies responsible for protected areas. For example, flights in the Ol Pejeta Conservancy in Kenya require not only operational permits from the KCAA [104] but also other wildlife conservation- and research-related approvals. These include permits from the National Commission for Science, Technology, and Innovation (NACOSTI), approval from the Wildlife Research Training Institute (WRTI), and letters of no objection from both Kenya Wildlife Services (KWS) and the conservancy management. Comparable multi-tiered approval processes are found in other regions,

underscoring the need for researchers to consult with local authorities and conservation agencies prior to initiating drone operations.

This dual-permission framework illustrates the necessity for a comprehensive understanding of both aviation and conservation regulations. Researchers are advised to engage proactively with the relevant authorities in the specific country of operation to ensure that all applicable permits and approvals are obtained before commencing fieldwork.

5. Key Challenges in Wildlife Responses to Drones

The increased use of drones in scientific research, conservation, and commercial practice presents several challenges to wildlife responses and the mitigation of drone-induced disturbance. Clarifying the challenges is crucial to informing guidelines that balance technological innovation and ethical wildlife conservation. The following are significant challenges to understanding and managing drone impacts on wildlife, providing a foundation for targeted future directions.

5.1. Species Responses and Long-Term Impacts of Drones

One of the primary concerns with wildlife surveying with drones is the inconsistency in species-specific responses and our incomplete understanding of long-term impacts. Species—and sometimes even individuals within the same species—differ greatly in response to drones, from immediate alertness and flight response to prolonged habituation. Sensitivity to both sound and visual stimuli; habitat; social context; and stage of life significantly influence these responses.

While short-term experiments can assess immediate behavioral reactions, little is known about long-term consequences of repeated or chronic exposure to drones. Repeated disturbances can possibly result in physiological stress build-up, displacement from critical habitats, or energy-allocation shifts that may reduce fitness and influence processes at the population level in the long term. For instance, prolonged exposure to drones at critical periods such as breeding, molting, or parental care may disrupt reproductive success, cause nest abandonment, or alter group behaviors. Alternatively, some species might become accustomed to the presence of drones over time, potentially modifying their natural anti-predator behaviors and making them vulnerable to other threats.

Future Research Need: It is necessary to develop a comprehensive and standardized framework for monitoring the effects of drones on various species across extended periods. This framework should collect species-specific information across diverse environmental contexts; investigate habituation response and behavioral adaptability; and track cumulative effects such as stress markers, reproductive rates, and changes in movement or behavior over time. An understanding of the effects of long-term repeated exposure will allow scientists to balance the benefits of drone use with wildlife welfare protection.

Proposed Approach: Meta-analyses and long-term research are needed to integrate knowledge about drone responses so that generalizable recommendations can be made that would be adaptable to specific species and contexts. Response in wildlife must be tracked through the use of technology such as GPS collars, remote cameras, and biometric sensors to document responses before, during, and after repeated exposure to drones. These efforts will provide a robust understanding of both species-specific variability and the cumulative long-term effects of drone use. Furthermore, incorporating stress-related physiological data, such as cortisol levels, together with behavioral data will provide us with an insight into how drone exposure affects wildlife health and fitness. Such research is required to inform sustainable activity, ethical guidelines, and policymaking for the effective use of drones in wildlife monitoring.

5.2. Limitations in Multi-Species Risk Assessment

Current research is predominantly focused on one species or on certain taxonomic groups, and little is done on the general ecological impact of drones on multi-species populations or ecosystems in general. As a result, risk assessments do not rely on full evidence on how drone activity affects various populations of wildlife and interspecies relations in shared habitats.

Future Research Need: Establish multi-species test protocols using diverse taxa and ecological interactions. Knowledge of the impact of drones on a variety of cohabiting species can improve conservation strategies.

Proposed Approach: Encourage cross-disciplinary collaborations comparing drone impact on various species and ecosystems and work toward formulating community-level or ecosystem-based recommendations.

5.3. Ethical and Conservation Considerations

The ethical concerns of using drones over wildlife areas necessitate careful evaluation. Chronic stress reactions in wildlife have the potential to impact health, reproductive success, and habitat use with prolonged exposure to drones, particularly in high-density tourist areas. This is especially relevant in protected or sensitive areas where conservation goals emphasize minimal human intrusion.

Future Research Need: Ethical guidelines and measures to mitigate disturbances must be set through the involvement of conservation stakeholders. This includes specifying drone-free zones and limitations on the use of drones in sensitive ecological regions.

Proposed Approach: Establish ethical guidelines for the deployment of drones based on non-intrusive approaches—for instance, quiet or biomimetic drones—and provide regulatory guidelines for safeguarding crucial habitats from drone disturbances.

5.4. Technological Constraints and Flight Precision

Current drone technology is limited in minimizing auditory and visual intrusions, particularly with multi-copter drone noise and flight precision needed for close-in surveillance. Noise pollution is an ongoing challenge, with varying impacts on species depending on their hearing range, habitat, and exposure to other anthropogenic sounds.

Future Research Need: Support research on quieter propulsion and adaptive flight algorithms with the aim of reducing noise and increasing precision.

Proposed Approach: Design less noisy, eco-friendly drones for wildlife monitoring with emphasis on noise-suppressing technology and improved in-flight control to reduce sudden, animal-alarming movements.

5.5. Regulatory Limitations

When planning drone operations for wildlife conservation, it is important to recognize that regulatory constraints and application procedures significantly influence what may be achieved in practice. As outlined in Section 4.6, each country implements its own regulatory framework through its national aviation authority, resulting in differences in requirements and procedures. Nonetheless, the guidance provided by international organizations such as ICAO, EASA, and the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) [105] has contributed to a certain degree of harmonization, particularly with respect to operational limitations.

Future Research Need: A notable challenge lies in the complexity and diversity of the application processes, which can vary markedly between countries. This is especially evident in developing nations where resources for modernizing and maintaining regulatory systems may be limited. Comprehensive studies are needed on how these various

regulatory regimes influence the efficiency and feasibility of conservation projects. Such studies should also examine the development of more adaptable and simplified regulatory processes that can be adjusted to fit the unique needs of wildlife conservation projects.

Proposed Approach: EASA regulations provide a widely adopted framework for drone operations and serve as a reference for many countries, particularly within Europe and in several African nations that are aligning their regulatory developments with international best practices. Simplification of the complexity of the application process in various regulatory environments would assist conservation groups in managing such issues more efficiently. This can be achieved by developing an international consensus on the minimum standards when applying for the use of drones in conservation efforts, encouraging nations to adopt more standardized application processes. Additionally, cooperating with global organizations will ensure the scope and applicability of guidelines, such as those of EASA, are extended.

For example, under EASA, drone operations are categorized into three main groups, each with defined criteria and associated operational restrictions that could be adapted to streamline conservation-related drone uses:

Open Category: This category is designed for low-risk operations and is subject to predefined limitations. To qualify, operations must be conducted within visual line of sight (VLOS), maintain a maximum altitude of 120 m AGL, and involve an unmanned aircraft with a maximum take-off mass (MTOM) of less than 25 kg. Operators are required to hold a corresponding competency certificate depending on the subcategory in which they intend to operate.

Specific Category Operations that do not meet the criteria for the open category must be authorized under the specific category. The preferred approach is to submit a pre-defined risk assessment (PDRA), which streamlines the approval process by using predefined safety requirements for common operational scenarios. However, due to its limited scope, many conservation operations require a more detailed custom risk assessment. The specific operations risk assessment (SORA) framework [106] , developed by JARUS, provides a structured 10-step process for identifying and mitigating both ground and air risks, thereby assisting in the formulation of safety objectives and containment measures. Alternatively, operators may follow a standard scenario (STS) if their operation aligns with an established predefined scenario, allowing for a simplified authorization process. Additionally, organizations with a light drone operator certificate (LUC) may self-authorize certain operations without requiring individual approvals, reducing administrative burdens.

Certified Category Although this category applies to very high-risk operations, its complexity renders it largely unsuitable for typical conservation applications and is therefore beyond the scope of this discussion.

In summary, aviation regulations and the associated risk assessment procedures impose significant limitations on the deployment of drones in wildlife conservation. The diversity in regulatory frameworks and application processes requires that research teams allocate considerable time and resources to secure both aviation and conservation permits. This complexity necessitates a thorough pre-operational review of local and international regulations to ensure that drone operations are conducted safely and in full compliance with all relevant standards.

6. Future Research Directions

There are several other aspects that warrant consideration in the future to enhance the ethical development of drone-assisted wildlife conservation. The following recommendations offer ways forward to enhance the effectiveness and ethical considerations of drone use in this domain.

6.1. Innovations in Drone Technology

As we progress in ethical drone usage towards wildlife conservation, there is more emphasis on continuous innovation. Future advances in drone technology must be directed at developing quieter propulsion systems, adaptive flight algorithms that minimize disturbance, and custom sensors that optimize data collection while reducing the effect on wildlife.

Cross-disciplinary collaboration between engineers, biologists, and conservationists will be needed to push the boundaries of drone design innovation in order to minimize the ecological footprint of future models. Additionally, drone swarms have tremendous potential in wildlife monitoring through the delivery of high-quality and multi-perspective data across large areas. However, the real-world deployment of such systems remains limited due to a lack of automated solutions capable of ensuring synchronization and coordination in diverse environments.

Swarm or multi-drone technology innovation also emphasizes coordinated intelligence as the answer to the limitations of individual-drone capability [107]. Deploying autonomous multi-drone missions could revolutionize wildlife research by increasing efficiency and reducing human intervention in fragile ecosystems. This is achievable if development continues on autonomous control systems that enhance cooperation between drones. This will enable data to be gathered and tracked in real time for social animals, particularly where human presence can disrupt animal behavior [108,109].

6.2. Tailoring Guidelines for Diverse Ecosystems

Considering the diversity of ecosystems, all subsequent work in the conservation of wildlife through drones needs to be geared toward establishing guidelines tailored to the specific needs of aerial, terrestrial, and aquatic environments. While it is impossible to test every habitat or species, a practical approach would be to focus on representative species, communities, or habitat types that capture a broad range of behavioral responses. Modeling based on such representative populations can aid in creating adaptable frameworks with generalized rules that are optimized for specific cases. Recommendations must account for unique sensitivities within each habitat, suggesting altitude and noise thresholds that respect wildlife behavioral intricacies and acoustic requirements. A nuanced approach to guidelines ensures adaptability across diverse ecosystems.

6.3. Global Collaboration and Standardization

The proposed way forward here is the advancement of international collaboration and standardization of ethical drone use in wildlife conservation. Collaboration across disciplines and between researchers, conservationists, and policymakers is necessary to share best practices, standardize ethical standards, and create an international code of practice for responsible drone-assisted wildlife monitoring. Standardization ensures ethical concerns are given equal consideration irrespective of geographical area or type of ecosystem.

6.4. Development of Testing Standards for Drones

Shaping the future of ethical wildlife monitoring requires establishing testing standards for drones. Proper testing of noise emissions, flight heights, and behavioral impacts on wildlife should be an integral part of a standardized test regime, ensuring adherence to approved ethical standards and encouraging accountability in wildlife conservation techniques. The recent advancement of drone technology [110] holds promise for biologists, as it offers the means to accurately quantify the immediate impacts of drones on animals. One example of software that can do this is the newly created WildBridge [111], which records real-time camera footage and telemetry data on any external interface, and tracks

proximity of drones to targets, thereby enabling a better and quicker estimation of animal reaction to the drone. Biomimicry concepts can also be investigated in testing procedures to evaluate the drone's ability to minimize disturbance by drawing inspiration from natural behaviors that animals display.

7. Conclusions

The increasing use of drones in wildlife research has provided significant advances in data collection, remote monitoring, and conservation efforts. However, this review recognizes the serious issues caused by drone disturbance to wildlife and urges evidence-based standards for operations to mitigate potential adverse effects. The impact of drones is extremely variable across species and ecosystems, which is guided by parameters such as flight altitude, velocity, distance, noise, and species-specific sensitivities. Though there has been much documentation of short-term behavioral and physiological responses to disturbance caused by drones, the long-term ecological effects remain to be exhaustively explored.

A synthesis of the literature highlights the critical importance of implementing standardized operating practices for ensuring the ethical and responsible use of drones in wildlife research. Flight parameters such as altitude, trajectory, and approach methods must be carefully optimized to reduce stress-induced responses while maintaining the integrity of ecological studies. Moreover, future research must employ longitudinal assessments to determine the cumulative effects of drone exposure on wildlife habitat use, reproductive success, and behavior. Additional advances in drone technology, including the creation of noise reduction technologies and biologically inspired design, may enhance the potential for unobtrusive aerial data collection.

Given the interdisciplinary nature of this field, collaboration among ecologists, engineers, conservationists, and regulating agencies is necessary to develop species-specific guidelines that balance research goals and animal welfare. Ethical considerations must remain central, ensuring that technological progress does not compromise ecological integrity. Addressing these challenges necessitates a concerted effort to evolve drone applications in wildlife research that enable impactful conservation with minimal anthropogenic disturbance. Standard risk assessments and robust regulatory frameworks must be the focus of future efforts to enable the sustainable implementation of drones in biodiversity monitoring and management.

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