Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology

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Unmanned aircraft systems (UAS) – also called unmanned aerial vehicles (UAVs) or drones – are an emerging tool that may provide a safer, more cost-effective, and quieter alternative to traditional research methods. We review examples where UAS have been used to document wildlife abundance, behavior, and habitat, and illustrate the strengths and weaknesses of this technology with two case studies. We summarize research on behavioral responses of wildlife to UAS, and discuss the need to understand how recreational and commercial applications of this technology could disturb certain species. Currently, the widespread implementation of UAS by scientists is limited by flight range, regulatory frameworks, and a lack of validation. UAS are most effective when used to examine smaller areas close to their launch sites, whereas manned aircraft are recommended for surveying greater distances. The growing demand for UAS in research and industry is driving rapid regulatory and technological progress, which in turn will make them more accessible and effective as analytical tools.

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Unmanned aircraft systems (UAS) are emerging as powerful tools in wildlife ecology, and can provide novel remote-sensing data at fine spatial and temporal scales (Anderson and Gatson 2013). Applications of UAS technology are diverse and growing, ranging from sampling airborne microbes, to locating wildlife poachers, to providing data on cetacean behavior and body condition. As the technology and regulatory frameworks improve, research applications are diversifying rapidly, and studies incorporating this technology are likely to proliferate in the future.

For a number of applications, UAS may increasingly replace manned fixed-wing aircraft and helicopters, which are popular tools for surveying animals and plants for research, conservation, and management purposes. While effective for covering large areas, manned aircraft are also expensive, disturb wildlife, and are the leading cause of work-related deaths among biologists (Sasse 2003; Wiegmann and Taneja 2003; Watts *et al.* 2010). Recent technological advances in UAS, combined with increasingly sophisticated remote-sensing equipment, are facilitating ecological research that may be safer, more cost-effective, and less invasive than traditional methods (Figure 1; Anderson and Gaston 2013).

The tendency of fixed-wing airplanes and helicopters to disturb wildlife is well-known (Andersen *et al.* 1989; Bleich *et al.* 1994; Delaney *et al.* 1999; Giese and Riddle 1999; Richardson 2002). Most wildlife researchers use small multicopter or fixed-wing UAS due to their affordability and maneuverability (Figure 1), and these small UAS are considerably quieter than manned aircraft and in general appear to cause minimal disturbances to wildlife if operated responsibly (Figure 2; Sardà-Palomera *et al.* 2012). However, accounts of UAS disturbing bighorn sheep (*Ovis canadensis*) in National Parks within the US have spurred a nationwide ban on the use of UAS by the US National Park Service (NPS; NPS 2014), raising broader concerns about wildlife photographers and enthusiasts who widely adopt UAS without proper training or regard for potential impacts on animals.

In a nutshell:

- Unmanned aircraft systems (UAS) are becoming increasingly common in wildlife research and may be less expensive, quieter, and safer than traditional manned aircraft
- Most studies we reviewed recorded minimal or no visible behavioral responses to UAS; however, UAS are capable of causing behavioral and physiological responses in wildlife when observing at close range
- In some cases, UAS can replace traditional surveys of wildlife and provide data with high levels of accuracy
- UAS are best used in studies where they can be deployed from nearby platforms to cover small areas, and are not well-suited for surveys of large areas
- Additional technological advances, combined with a more streamlined regulatory process, will likely transform the way we collect ecological information in the future

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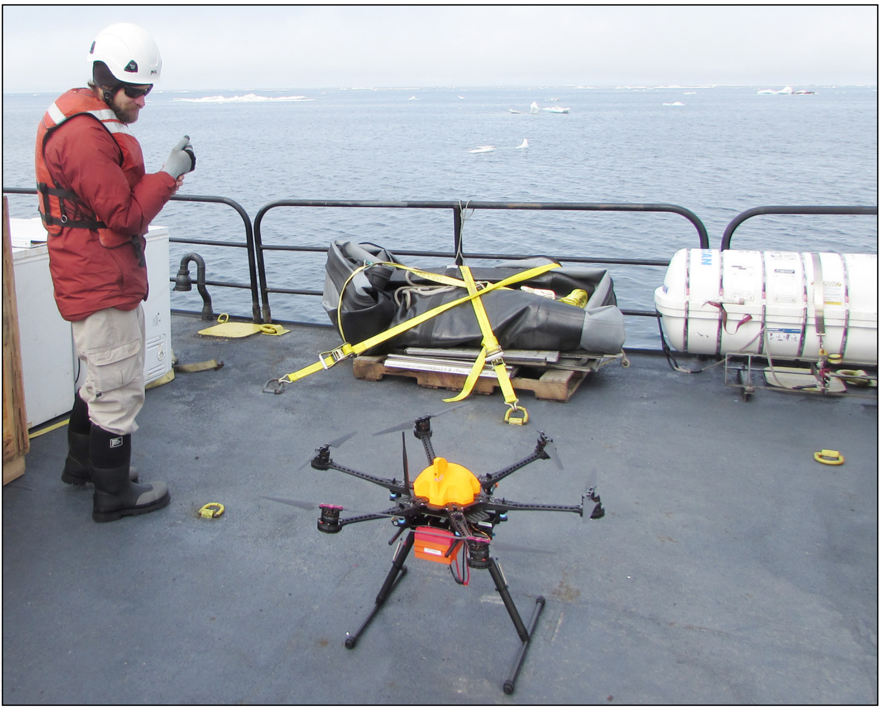

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Figure 1. *A Ptarmigan multicopter unmanned aircraft system (UAS) equipped with a stabilized high-resolution camera, used for USGS vessel-based surveys of walruses.*

Small UAS have the advantage of being cost-effective, fuel-efficient, and able to access dangerous or inhospitable areas. These types of UAS are either battery or fuel powered, and – due to their limited size – have lower power requirements than manned aircraft. As a result, small UAS operate at a fraction of the cost of manned aircraft but with greatly reduced flight ranges (Hodgson *et al.* 2013). Nevertheless, scientists are able to conduct repeat surveys using UAS, which allow for more accurate population estimates (Sardà-Palomera *et al.* 2012). Repeat surveys are further facilitated by the ability of UAS to consistently follow precise, predetermined flight paths (Watts *et al.* 2010). Moreover, their small size and the absence of a human pilot and observer onboard allow UAS to fly at low altitudes over dangerous areas such as islands, rough waters, and regions where illegal poaching or logging occurs (Koski *et al.* 2009; Sardà-Palomera *et al.* 2012; Mulero-Pázmány *et al.* 2014).

The use of remote-sensing equipment mounted on UAS can increase the precision and accuracy of estimates of wildlife population size. For instance, thermal cameras detect animals based on their body heat and have the advantage of identifying animals that are not easily visible to the naked eye. UAS equipped with thermal cameras could be extremely useful for detecting cryptic nocturnal species such as owls and felids, and this technology has been used successfully to detect and estimate abundance of deer (*Odocoileus virginianus* [Potvin and Breton 2005; Kissell and Nimmo 2011] and *Capreolus capreolus* [Israel 2011]) and caribou (*Rangifer tarandus* [Carr *et al.* 2010]). In addition to detecting cryptic species, such remote-sensing approaches minimize observer fatigue and produce a permanent record of the data, which can be reviewed multiple times for quality-control purposes (Hodgson *et al.* 2013). Similar to having a security camera record criminal activity, a permanent recording of an ecological or wildlife survey provides an objective, enduring record of the organism of interest for future reference, data sharing, and further analysis. However, as with other data-intensive methods, standardized metadata and long-term archiving will be crucial to maintaining the usefulness of such records.

In many cases, the advantages of using small UAS for wildlife research are outweighed by major limitations in flight range due to both technological and legal factors. Current Federal Aviation Administration (FAA) regulations as well as battery life markedly restrict the distance that a UAS is able to cover, particularly for multirotor UAS (Watts *et al.* 2010; Anderson and Gaston 2013; Hodgson *et al.* 2013; Mulero-Pázmány *et al.* 2014). Medium and large UAS have greater fuel capacity, but the cost is likely to be prohibitive for most scientific researchers. Additionally, technological limitations, data-processing time, and uncertainty as to how UAS affect wildlife may also pose obstacles to their widespread use by scientists.

In this paper, we synthesize published and original research featuring novel applications of UAS in wildlife research, and weigh the advantages and disadvantages of this technology. We describe how UAS have been used to gather information on terrestrial and marine wildlife and their habitats; additional information on fisheries research and monitoring for conservation and management is provided in WebPanel 1. Further, we compare the cost, sound production, and operating range of different manned and unmanned vehicles using data from the Alaska Center for Unmanned Aircraft Systems Integration (ACUASI), the US Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA).

Comparisons of different models of UAS and manned aircraft

Due to their diverse sizes and payloads, UAS vary substantially in speed, range, cost of operation, and noise emissions. For example, at an altitude of 100 m, a large UAS (the US Army Shadow fixed-wing) produced sound levels of 84 dBA (A-weighted decibels); a medium UAS (the ScanEagle fixed-wing) produced 66 dBA; and a small UAS (the Aeryon Scout quadcopter and the Raven fixed-wing) produced 55 dBA and 50 dBA, respectively (Figure 2). By comparison, helicopter noise levels were approximately 95 dBA, and manned fixed-wing aircraft varied from 75–88 dBA, depending on the aircraft. The cost to purchase a small multicopter UAS can range from $300 for a basic, commercially available model to more than $100,000 for a custom model designed for research (WebTable 1). Fixed-wing UAS costs extend from $2000 for smaller models to $16.9 million for large, long-range, military-grade models. Manned aircraft cost upwards of $60,000 to purchase, and hourly rates vary between $600–3000 per hour, depending on type (helicopter or fixed-wing) and size (WebTable 1). With the exception of the large US Army Shadow, UAS were much slower (50–204 kilometers per hour [kph]) than manned aircraft (223–332 kph). UAS varied in survey time from 0.5 hours for a small multicopter UAS to 24 hours for the large US Army Shadow UAS (WebTable 1). Manned aircraft could remain airborne for 2–7 hours (WebTable 1). In terms of distance, the operating range of UAS and manned aircraft varied from 3 to 6000 km and from 439 to 2112 km, respectively. UAS could carry payloads of 0.5 kg (small multicopter) to 907 kg (large NASA Ikhana), whereas manned aircraft could carry heavier payloads of 760 to 2118 kg (WebTable 1).

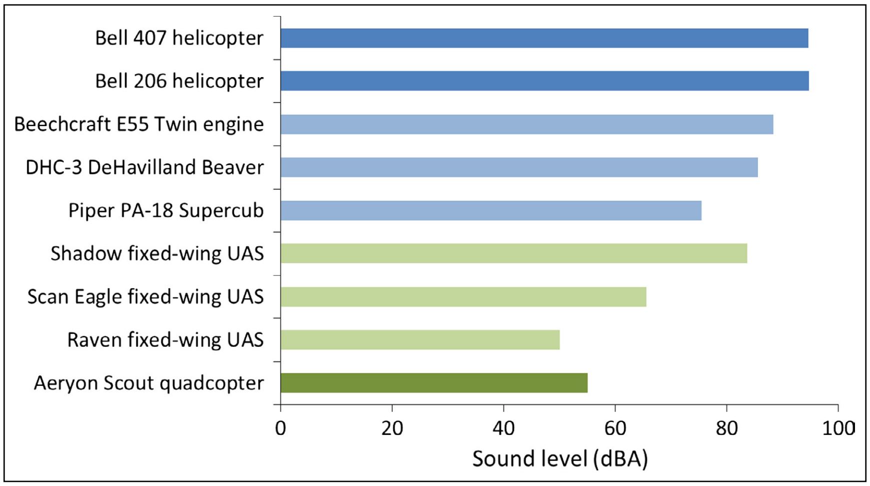

Figure 2. *Sound levels (dBA) of different models of UAS, fixed-wing aircraft, and helicopters. For each type, sound levels were obtained as follows: for the Aeryon Scout quadcopter (recorded by the authors using a Larson-Davis 831 decibel reader), for the Raven UAS (obtained from USGS), for the Scan Eagle UAS (from Hodgson* et al. *2013), for the Shadow UAS (from US Army 2004), and for all manned aircraft (from FAA 1988). We adjusted sound levels at different altitudes, to a common altitude of 100 m using this equation:* 20 × log(altitude of measurement ÷ desired altitude) + measured sound level. *Sound levels were recorded in A-weighted decibels, which reduce the decibel values of sounds at very low frequencies.*

■ Terrestrial wildlife

Researchers interested in the ecology of terrestrial animals have long relied on aerial surveys to quantify their abundance, distribution, and habitat. Recently, UAS have been used to carry out these key functions, and to capture data that were previously difficult to collect using manned aircraft. Count-based estimates of abundance have been obtained by UAS for waterbirds at wildlife refuges (USGS 2014), white pelican (*Pelecanus erythrorhynchos*) breeding colonies (USGS 2014), sandhill crane (*Grus canadensis*) migratory stopover sites (USGS 2011), snow goose (*Chen caerulescens*) and Canada goose (*Branta canadensis*) flocks (Chabot and Bird 2012), and greater sage-grouse (*Centrocercus urophasianus*) lek sites (Hanson *et al.* 2014) (WebTable 2). In studies of common terns (*Sterna hirundo*) and sandhill cranes, counts obtained from UAS were within 6% and 5% of counts from ground-based surveys, respectively (USGS 2011). Another promising application of UAS for avian ecology involves the characterization of flight paths and habitat selection, as demonstrated by Rodríguez *et al.* (2012), who equipped foraging lesser kestrels (*Falco naumanni*) with Global Positioning System (GPS) loggers, enabling UAS to follow the GPS tracks in near-real time. Finally, UAS are increasingly being relied upon to access nest sites. Studies quantifying the reproductive success of birds nesting above ground level are challenging, and often involve human observers climbing to nest sites to monitor egg and nestling survival. In a study of hooded crows (*Corvus cornix*), the use of UAS resulted in lower levels of disturbance as compared with traditional climbing surveys (Wessensteiner *et al.* 2015). UAS platforms used to study birds included both fixed-wing and multicopter designs, and flight altitudes ranged from 30–183 m, with variable airspeeds (range: 15–80 kph; WebTable 2). Sampling technology included still and video imagery in visible wavelengths, as well as two applications of infrared (IR) videography to count sandhill cranes at roost sites overnight (L Hanson, unpublished data) and to detect greater sage-grouse during predawn in low light conditions (Hanson *et al.* 2014).

Overall, of the 13 UAS-based avian studies reviewed in this paper (WebTable 2), seven collected behavioral observations, with bird reactions to UAS ranging from no response (*n* = 1 study; snow and Canada geese), to minimal to no response (n = 5 studies; greater sage-grouse, sandhill cranes, black-headed gulls, common terns, mallard ducks, and flamingos), to moderate response (n = 1 study; hooded crows). Most bird responses to UAS appear to be transient, but more research is needed to explicitly test the reactions of different species to this technology, and to quantify non-visible but possibly important stress responses. In addition, behavioral responses in some studies varied by UAS flight characteristics or time of day. For example, in one study testing behavioral responses of waterbirds, UAS were able to approach to within 4 m of birds without disturbing them on 80% of flights, and birds reacted more strongly to UAS approaching vertically than horizontally (Vas *et al.* 2015). In another study, migrating sandhill cranes were not disturbed if flights occurred while the birds were roosting but were temporarily disturbed if UAS approached while the birds were loafing and feeding (L Hanson, unpublished data).

Terrestrial mammals have also been effectively surveyed with UAS. Abundance and distribution surveys have been conducted for elk (*Cervus elaphus*; USGS 2014), deer (*Cervus* spp, *Dama dama*; Israel 2011; Barasona *et al.* 2014), orangutans (*Pongo pygmaeus*; Koh and Wich 2012; Van Andel *et al.* 2015), elephants (*Loxodonta africana*; Vermeulen *et al.* 2013), and rhinoceros (*Diceros bicornis* and *Ceratotherium simum*; Mulero-Pázmány *et al.* 2014) (WebTable 2). Fixed-wing UAS platform designs predominated, likely because of the extensive home ranges associated with these large mammalian species. Altitude of surveys varied considerably (30–183 m), and sampling included digital and IR wavelengths in both video and still format (WebTable 2).

Similar to birds, mammals appeared to show minimal behavioral responses to UAS, although experiments are needed to explicitly test this for a variety of species. Of the six studies that directly surveyed terrestrial mammals (rather than focusing on habitat), three included behavioral responses in their results (WebTable 2), and these ranged from no response (n = 2; elephants and rhinos) to moderate to high response (n = 1; black bears [*Ursus americanus*]). Importantly, black bears often exhibited minimal visible response to UAS, but still had elevated heart rates, indicating that physiological stress responses may occur without a visible behavioral cue (Ditmer *et al.* 2015). Given the interest within the wildlife research community to develop alternative survey methods for ungulates, we tested for UAS-induced behavioral changes in captive caribou and semi-domesticated reindeer (both *Rangifer tarandus;* hereafter "caribou"). Animals were exposed to an Aeryon Scout quadcopter flying at an altitude of 60 m (WebTable 2). Overflights lasted approximately 30 seconds to 2 minutes, and each animal was exposed to a maximum of two overflights. Scan samples (15 total) conducted on 33 caribou before and during UAS flights indicated that the animals did not change their activity patterns when exposed to a UAS flying overhead ($t_{\text{all}} < 1.2$, $P_{\text{all}} > 0.25$; Figure 3). However, because these caribou were in a captive setting, and had been exposed to anthropogenic noise, they may have been less sensitive to UAS noise as compared with wild caribou. Nevertheless, our data suggest that caribou in the wild would either (1) not respond behaviorally to UAS overflights, or (2) respond initially but habituate to such flights.

■ Marine wildlife

Marine species are notoriously difficult to study, and manned aircraft have played a key role in investigations of their distributions, movements, abundance, and body condition. Advances in UAS technology have made it possible to successfully survey marine mammals at primary feeding, birthing, and haul-out areas up to 150 km from shore (Koski *et al.* 2009). Similar to the constraints of manned aerial surveys, detection of mammals by UAS surveys is strongly dependent on wave conditions and the color of the animal, and is maximized by high-resolution imagery (Koski *et al.* 2009). Dugongs (*Dugong dugon*), sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), and bowhead whales (*Balaena mysticetus*) have been successfully surveyed using fixed-wing and multicopter UAS fitted with high-resolution digital cameras (WebTable 2; Hodgson *et al.* 2013; NOAA 2014a; Durban *et al.* 2015; Koski *et al.* 2015). In addition to counting marine mammals, useful information on body condition, age, and sex can be obtained. For instance, NOAA scientists used a multicopter equipped with a digital camera to photograph and later identify individual resident killer whales, while simultaneously quantifying their body size and diagnosing pregnancies (Figure 4a; NOAA 2014b). The multicopter hovered 30 m above the whales without disturbing them, and provided greater resolution for measuring body condition and length as compared with traditional helicopter surveys (Fearnbach *et al.* 2011; Durban *et al.* 2015). In addition, a fixed-wing UAS was used successfully to photograph and later identify individual bowhead whales without causing any observable disturbance to the animals (Koski *et al.* 2015). Likewise, in photo-identification studies, the slower speed of the UAS as compared with manned aircraft facilitates the capture of high-resolution images with less blur (Koski *et al.* 2015). Finally, Bevan *et al.* (2015) were able to locate and monitor hatchling and adult sea turtles with the aid of a GoPro camera mounted on a small quadcopter UAS operating at heights of 30–50 m, and recorded no behavioral responses to the UAS among the turtles.

Given their low noise production and ability to access remote, dangerous locations, UAS may be particularly useful for surveying marine wildlife at haul-out sites and breeding colonies. There is much concern about the tendency of hauled-out marine mammals to stampede or

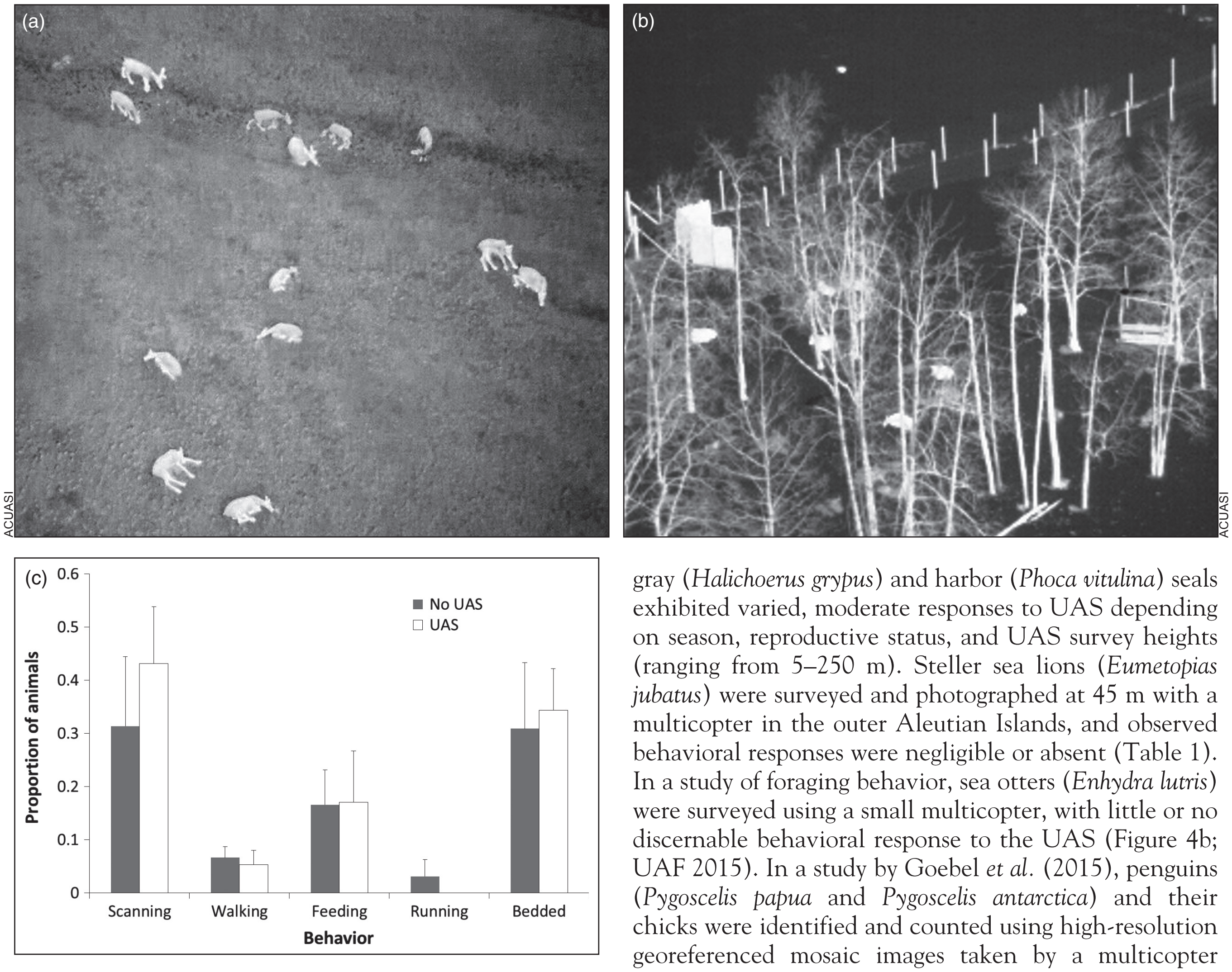

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Figure 3. *Infrared images taken with an Aeryon Scout UAS of caribou (a) in an open field and (b) in a patch of forest. Also shown are observations of caribou behavior before and during UAS flights (c). A total of 15 scan samples were collected from 33 captive animals at the Large Animal Research Station at the University of Alaska Fairbanks. Error bars denote standard errors. No statistically significant difference in behavior was detected between UAS and no-UAS time periods.*

otherwise move into the water when disturbed by a low-flying fixed-wing aircraft (Born *et al*. 1999; Udevitz *et al*. 2013). Walruses (*Odobenus rosmarus divergens*) are particularly prone to stampede, and large numbers have been killed at haul-out sites during stampede events in recent years (Udevitz *et al*. 2013). UAS produce substantially less sound (50 dBA for a small fixed-wing UAS at an altitude of 100 m) than manned aircraft (75 dBA at the same altitude; Figure 2), and may therefore circumvent this problem (Hodgson *et al*. 2013). Moreland *et al*. (2015) surveyed spotted (*Phoca largha*) and ribbon (*Histriophoca fasciata*) seals at 122 m using digital single-lens reflex cameras, and found little to no behavioral response. In contrast, Pomeroy *et al*. (2015) reported that gray (*Halichoerus grypus*) and harbor (*Phoca vitulina*) seals exhibited varied, moderate responses to UAS depending on season, reproductive status, and UAS survey heights (ranging from 5–250 m). Steller sea lions (*Eumetopias jubatus*) were surveyed and photographed at 45 m with a multicopter in the outer Aleutian Islands, and observed behavioral responses were negligible or absent (Table 1). In a study of foraging behavior, sea otters (*Enhydra lutris*) were surveyed using a small multicopter, with little or no discernable behavioral response to the UAS (Figure 4b; UAF 2015). In a study by Goebel *et al*. (2015), penguins (*Pygoscelis papua* and *Pygoscelis antarctica*) and their chicks were identified and counted using high-resolution georeferenced mosaic images taken by a multicopter UAS flying at 60-m altitude; UAS-derived counts were within 5% of traditional ground-based surveys, and the penguins were not disturbed. Overall, of the 13 studies that we found on marine wildlife, seven examined behavioral reactions, which ranged from no response (n = 4; killer whales, bowhead whales, leopard [*Hydrurga leptonyx*] and fur [*Arctocephalus gazella*] seals, penguins) to minimal to no response (n = 2; Steller sea lion, ribbon and spotted seals), to moderate response (n = 1; gray and harbor seals).

■ Spatial ecology

Advances in technology – such as higher payload capacity of small UAS and miniaturization of multispectral and hyperspectral sensors in conjunction with improved computer-processing capabilities – have allowed practitioners to monitor habitat for fish and wildlife species. Data collected through traditional remote-sensing techniques (eg manned aircraft or satellite) are often too coarse in resolution to suit fine-scale ecological studies (Wulder *et al*. 2004). Commercially operated satellite sensors can now

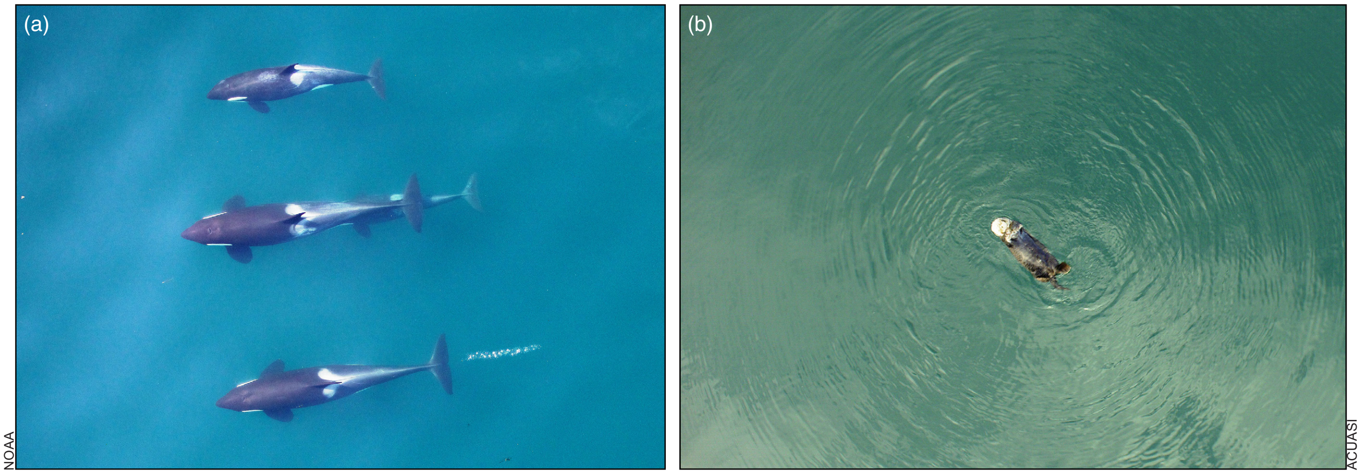

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Figure 4. *Photographs taken from UAS demonstrating (a) a group of killer whales (platform: APH-22 hexacopter, study by NOAA) and (b) a foraging sea otter (platform: Aeryon Scout, study by the University of Alaska Coastal Marine Institute).*

produce data at finer resolutions; however, operational constraints include prohibitively high costs associated with acquiring images, cloud contamination of regions of interest, and the inability to repeat measurements over required timescales (Loarie *et al.* 2007). It has been argued that UAS equipped with remote-sensing payloads (eg RGB cameras, color IR sensors, and light-weight thermal systems) may help to resolve issues associated with spatial ecology (Anderson and Gaston 2013). Small UAS can hover at lower altitudes to capture fine-scale habitat metrics such as forest canopy gaps and understory plant diversity (Getzin *et al.* 2012). Additionally, the flexible maneuverability of UAS may circumvent issues associated with cloud contamination and minimize time between site revisits (Herwitz *et al.* 2004).

Fine-resolution remotely sensed data obtained via UAS have been used to quantify habitat characteristics in a number of studies. For example, habitats of wetland birds, including the US federally listed Yuma clapper rail (*Rallus longirostris yumanensis*) and southwestern willow flycatcher (*Empidonax traillii extimus*), were mapped using color IR to capture NDVI (normalized-difference vegetation index) and subsequently classify vegetation (Figure 5; USGS 2014). Sage-brush habitat for another endangered species, the pygmy rabbit (*Brachylagus idahoensis*), was also successfully mapped with a UAS using visible-spectrum digital still photography (WebTable 2; Breckenridge *et al.* 2011; Levy 2011). Imagery obtained via UAS has also been applied to delineate localized cover types, estimate percentage of bare ground (Breckenridge *et al.* 2011), catalog forest composition (Dunford *et al.* 2009), and calculate leaf area index and chlorophyll content (Figure 5; Berni *et al.* 2009; McGwire *et al.* 2013). Furthermore, UAS equipped with IR or high-resolution cameras have been used to monitor the distributions of invasive species (Zaman *et al.* 2011; Wan *et al.* 2014), produce vegetation maps (Laliberte *et al.* 2011), and identify forest canopy mortality (Dunford *et al.* 2009).

■ Case studies

To illustrate the advantages and disadvantages of UAS technology in specific settings, we present two case studies. The first study documents the use of an APH-22 hexacopter to survey sea lion haul-outs and rookeries in the outer Aleutian Islands in Alaska (Table 1). The UAS was used to survey areas that were otherwise inaccessible by traditional survey methods (Twin Otter fixed-wing plane) due to inclement weather, remoteness, and a lack of suitable landing sites, and resulted in the most comprehensive survey of Steller sea lions in the Aleutians since the 1970s (K Sweeney, pers comm). Researchers launched the UAS from a vessel that was close (<1 km) to rookeries, and were able to capture high-resolution imagery of individual animals while causing minimal disturbance (Table 1). After an initial investment of $25,000 to purchase the UAS, the cost of the UAS program consisted primarily of operating the research vessel, and was less than the cost of operating the Twin Otter, given the multiple projects that shared the expense of running the vessel (Table 1). Although the UAS could survey rookeries that were inaccessible by the Twin Otter, the major disadvantage of the UAS was its dependence on a research vessel and its limited range: only 30 sites (400 km of coastline) were surveyed as compared to 201 sites (2500 km of coastline) surveyed by the Twin Otter over a similar time period.

In our second case study, researchers compared surveys of roosting sandhill cranes – at Monte Vista National Wildlife Refuge in Colorado – using a fixed-wing Raven RQ-11A UAS versus relying on ground-based surveys (Table 2). The UAS surveyed the same 38-ha area as

Table 1. Case study 1: comparison of traditional and UAS surveys of Steller sea lions in Alaska

	Manned aerial surveys	*UAS surveys*
Purpose of surveys	Estimate the abundance of Steller sea lions in the inner Aleutians	Estimate the abundance of Steller sea lions in the outer Aleutians
Cost per day	$4700 per day including fuel and pilot, or $400 per site	$3000 per day based on the cost of vessel support, or $1700 per site
Type of aircraft	NOAA Twin Otter	APH-22 hexacopter
Distance/area surveyed	2500 km of coastline, including the Gulf of Alaska and part of Aleutians; 210 sites surveyed	400 km of coastline along the western Aleutian chain, 30 sites surveyed; maximum distance from the vessel was 634 m, longest flight was 16 minutes
% animals detected	100% of hauled-out animals	100% of hauled-out animals
Data collected	Quantitative imagery, animal counts	Quantitative imagery, animal counts, individual identification
Number of personnel	6	2
Observed effect on animal	Slight and variable, 5% of adults moved toward water	Very low to none, 0.3% of adults moved toward water
Advantages	(1) surveyed up to 50 sites per day (2) high-quality images (3) cost per site low	(1) surveyed remote sites with no airfields (2) extremely low disturbance (3) very high-quality images (flew at altitude of 45 m) (4) less subject to flight restrictions due to weather (5) biologists can double as pilots
Disadvantages	(1) requires good weather at primary and alternate airfields (minimum of 750-ft ceilings) (2) relatively noisy (3) may only fly on half (or less) of days available (4) requires a runway for takeoff/landing (5) imagery has lower resolution (flight altitude: 150–305 m) (6) requires flight crew of 3 plus 3 observers	(1) can survey only a few (1–3) sites per day (2) requires costly vessel for use as transport (3) cannot fly in high winds (wind speed must be less than 25 knots on the ground) (4) must stay within line-of-sight and 0.8 km of observer

Notes: Surveys were conducted by the National Oceanic and Atmospheric Administration.

ground surveys, with no observable effect on crane behavior and a difference of 4.6% in accuracy between survey methods. UAS surveys used half the number of observers and therefore cost half as much to conduct. The Raven was owned by the US military, so a UAS purchase price was not factored into the cost estimates. Disadvantages of the UAS included the inability to fly during high winds or heavy rains, the requirement to fly within line-of-sight, and a lengthy flight approval process (Table 2).

Limitations of UAS technology

Major limitations to the widespread adoption of UAS include difficulties in obtaining permits for use, limited survey range, and data-processing time. Many of the small, battery-powered multicopters that are favored due to their low costs, energy efficiency, and ease of operation must be recharged or have batteries replaced approximately every 20 minutes, thereby restricting survey range. Larger UAS are capable of longer flights and greater payloads but are prohibitively expensive for most researchers (WebTable 1). Furthermore, many small UAS cannot currently be flown safely during severe weather conditions (Weissensteiner *et al.* 2015).

Lengthy, complex permitting processes required by national aviation authorities constrain UAS-based ecological research in the US (Vincent *et al.* 2015) and elsewhere around the world. In addition, many government permitting frameworks require that the UAS be operated within line-of-sight only (Watts *et al.* 2010; Anderson and Gaston 2013; Hodgson *et al.* 2013; Hanson *et al.* 2014; Mulero-Pázmány *et al.* 2014). This restriction reduces the survey range of a UAS beyond the limitations imposed by fuel or battery capacity (Table 1; Mulero-Pázmány *et al.* 2014). Nevertheless, some restrictions are necessary to ensure privacy, minimize the chance of aircraft collisions, and avoid harassing wildlife. Already, UAS have been used irresponsibly by civilians to approach wild animals, necessitating the introduction of strong regulations to protect wildlife from harassment in

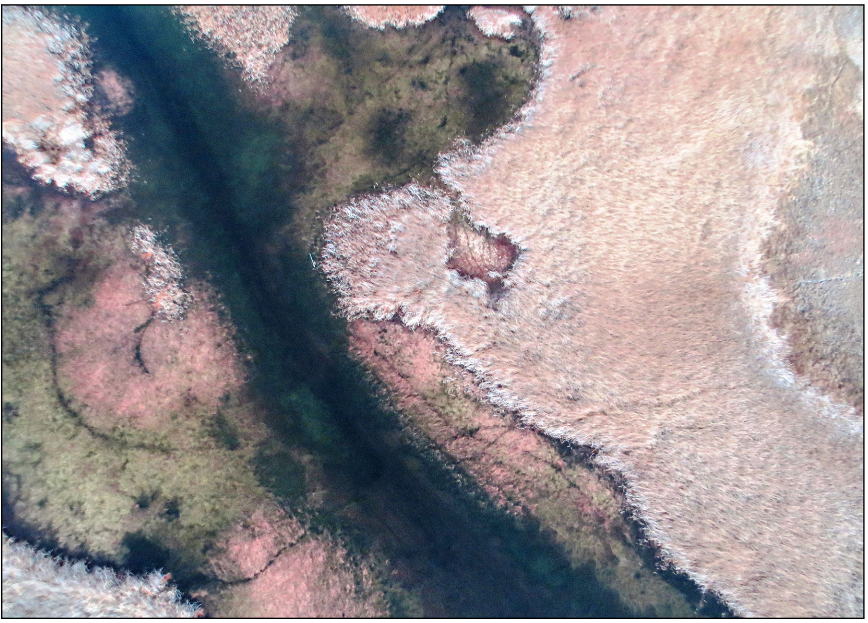

Figure 5. *A color infrared (IR) image of wetland vegetation used to identify habitat for US federally listed wetland birds. Color IR images were used to generate NDVI values, which in turn were used to classify habitat types.*

US National Parks. The NPS has issued a park-wide ban on the use of UAS – with an exception for scientific research conducted by park employees – due to visitor complaints of UAS disturbing wildlife and creating unwanted noise (NPS 2014). UAS operators have suggested regulations that limit operations to areas of low human density and aircraft traffic, or the designation of UAS corridors (Mulero-Pázmány *et al.* 2014).

Another current limitation of UAS involves the processing of large amounts of data generated by surveys. Digital photos, video, and other remote-sensing data often require a substantial time investment for data organization and processing; however, automated programs have been developed to improve the efficiency of this procedure (Groom *et al.* 2011; Dehvari and Heck 2012). In addition, the effectiveness of UAS in replicating results obtained by traditional surveys of wildlife is currently being debated, and the accuracy and precision of UAS-derived population estimates is being tested. Promisingly, recent research on the effectiveness of UAS in estimating wildlife population parameters (eg Koski *et al.* 2009; USGS 2011; Martin *et al.* 2012; Goebel *et al.* 2015) shows that this technique can indeed be highly accurate.

A key area for future research will be testing the effect of UAS on behavioral and physiological responses of different species of wildlife. Among the studies we analyzed, we found that UAS disturbed wildlife less than traditional methods when direct comparisons were made, although behavioral and physiological responses to UAS occurred in some situations. Of particular concern are species adapted to avian predators, as well as birds of prey themselves, some of which have been known to attack airborne UAS. Though quieter than traditional fixed-wing or rotor aircraft at comparable distances, UAS often approach animals more closely and therefore may have a greater impact in certain scenarios. Moreover, animals may become more disturbed by the sudden occurrence of noise from a UAS than by a slowly approaching manned aircraft, presenting another topic that warrants further investigation.

Conclusions and future directions

The burgeoning application of UAS in ecological and wildlife studies demonstrates that a growing number of scientists are embracing this novel technology to meet their needs. This technology has been used successfully to address a broad diversity of ecological research and management problems, and can be a cost-effective, safe, relatively quiet, and effective alternative to traditional survey techniques. Despite the advantages of conducting field research with UAS, major obstacles to their widespread adoption by ecologists include regulatory limitations, data-processing time, and fuel capacity or battery life. At this time, UAS are best suited to situations where they can be launched from platforms or areas that are relatively close to the target, and are not suited for surveys of large areas.

The future utility of UAS for ecologists is expected to be determined by the regulatory framework of the aviation administrations within each country in which they are operated, rather than by technological limitations (Vincent *et al.* 2015). In most countries, UAS must be operated within line-of-sight and lengthy permitting processes are necessary (Anderson and Gaston 2013; Linchant *et al.* 2015). However, regulations are changing; in February 2015, the FAA released proposed guidelines for civilian use of UAS in the US, requiring a single, certified operator rather than a trained UAS pilot (FAA 2015). In addition, administrations are considering regulations that include UAS flights outside of line-of-sight, an important step if they are to become widely used by ecologists. Commercial pressure on aviation administrations is intense, and the UAS industry is expected to expand to over 100,000 jobs by 2025, with an economic impact of $82 billion (Jenkins and Vasigh 2013; Tast 2015).

UAS will likely become increasingly popular in ecological research, as technological improvements allow long-distance, highly accurate flight trajectories and

Table 2. Case study 2: comparison of ground-based population abundance estimates with small UAS surveys of sandhill cranes in Colorado

	Ground-based surveys	*UAS surveys*
Purpose of surveys	Estimate the one-night abundance of roosting sandhill cranes at Monte Vista National Wildlife Refuge, Colorado	Estimate the one-night abundance of roosting sandhill cranes at Monte Vista National Wildlife Refuge, Colorado
Cost per day	$840.00	$400.00
Type of aircraft	N/A – optical count from ground	Raven RQ-11A
Distance/area surveyed	37.75 hectares (93.28 acres)	37.75 hectares (93.28 acres)
% animals detected	Overestimated number by 4.6%	100%
Data collected	Animal counts	Quantitative imagery, animal counts
Number of personnel	6	3
Observed effect on animal	No discernible effect	No discernible effect
Advantages	(1) low technology (2) easy to gather data – no computer required (3) can collect data in all types of weather	(1) low disturbance (2) imagery to verify counts (3) biologist can be UAS pilot
Disadvantages	(1) difficult to partition individual observer viewshed – can lead to overestimate of abundance (2) view can be obstructed by vegetation and lighting (3) count cannot be validated with imagery	(1) cannot fly in high winds (ground wind speed must be less than 25 knots) (2) flights delayed by rain (3) must stay within line-of-sight (4) may take long time for flight approvals

Notes: Surveys were conducted by the US Fish and Wildlife Service and the US Geological Survey.

diverse payloads, including various forms of remote-sensing equipment. Future applications for wildlife ecology include detecting and monitoring nests, dens, predator kill sites, and birth and mortality sites, as well as relocating radio- or GPS-tagged wildlife. In addition, UAS could potentially be harnessed to immobilize large-bodied wildlife using UAS-fired tranquilizers, collect biological samples (such as hair, breath, blood, scat, and saliva), track the illegal trade in wildlife products throughout the supply chain, and reduce wildlife–human conflict through negative conditioning of so-called "problem" animals. If the above-described limitations are overcome through further technological advances, a more streamlined permitting process, and continued research of the effects on wildlife, UAS have the potential to transform the way we collect ecological information.

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