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

Katherine S Christie1*, Sophie L Gilbert1, Casey L Brown1, Michael Hatfield2, and Leanne Hanson1

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.

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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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).

### 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, 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

![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.](image-url)
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 rhinoceroses (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 (r_all < 1.2, P_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 hatching 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
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...
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 (e.g., RGB cameras, color IR sensors, and lightweight 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
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
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

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.
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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**References**


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

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


Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1281/suppinfo