

A Review of Unmanned Aerial Vehicles Usage as an Environmental Survey Tool within Tidal Stream Environments

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Supplementary Table S1 Literature examined, in relation to multirotor UAV advantages and limitations of use, detailing origin, purpose, and summary of work.

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Lieber et al., 2019	[19]	Localised anthropogenic wake generates a predictable foraging hotspot for top predators	Queen's University Marine Laboratory, Portaferry, UK	- To quantify the relative use of an anthropogenically-generated wake by surface foraging seabirds, verified using UAV transects and hydroacoustics.	- Findings highlight the importance of identifying the physical scales and mechanisms underlying predator hotspot formation when assessing the ecological consequences of installing or removing anthropogenic structures.
Lieber et al., 2021	[23]	A bird's eye view on turbulence: Seabird foraging associations with evolving surface flow features	Queen's University Belfast, Portaferry, UK	- To track foraging terns across the wake of a monopile structure using hovering UAV surveys.	- The UAV-based approach, tracking seabirds and underlying physical features in synchrony, revealed new insights into localized tern foraging strategies among turbulence.
Chabot and Bird, 2015	[25]	Wildlife research and management methods in the 21st century: Where do unmanned aircraft fit in?	Avian Science and Conservation Centre of McGill University, Quebec, Canada	- To present a standard review of the existing wildlife-related literature involving UAVs, focusing on major categories of application as well as common methods of UAV operation, data collection and processing.	- UAVs prove to be useful as a convenient, timely, and unobtrusive means of surveying wild animals and their habitats in areas that are hard to access or navigate.
Anderson and Gaston, 2013	[26]	Lightweight unmanned aerial vehicles will revolutionize spatial ecology	Environment and Sustainability Institute, University of Exeter, Cornwall, UK	- To review current approaches to UAV deployment, summarise their demonstrated and potential applications, and suggest new ways in which UAVs could be used to underpin novel, scale-appropriate, environmental science research.	- UAVs offer scientists new opportunities for scale-appropriate measurement of ecological phenomena, delivering fine spatial resolution data at user-controlled revisit periods.
Hendrickx et al., 2011	[27]	The use of stereoscopic images taken from a	Ghent University, Ghent, Belgium	- To test if UAVs can provide a contribution to the photogrammetric documentation of heritage sites.	- The use of stereoscopic images taken from a microdrone for the documentation of heritage has

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		microdrone for the documentation of heritage – An example from the Tuekta burial mounds in the Russian Altay			proven to be successful. There were no problems with data acquisition once the right configurations had been set.
Christie et al., 2016	[28]	Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology	University of Alaska Fairbanks, Fairbanks, USA	- To synthesize published and original research featuring novel applications of UAVs in wildlife research and examine the advantages and disadvantages of this technology.	- UAV 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.
Barnas et al., 2020	[29]	A standardized protocol for reporting methods when using drones for wildlife research	University of North Dakota, Grand Forks, USA	- To outline a proposed protocol for reporting methodological details of UAV-based data collection in wildlife research.	- The current version of this protocol can assist with the communication, dissemination, and adoption of UAV technology for wildlife research and management.
Wolinsky, 2017	[30]	Biology goes in the air	Chicago, USA	- To detail examples of UAV usage within conservation and environmental research.	- UAVs may have an important role in wildlife management, but there are concerns that UAVs might adversely affect wildlife.
Rush et al., 2018	[31]	Can drones count gulls? Minimal disturbance and semiautomated image processing with an unmanned aerial vehicle for colony-nesting seabirds	University of York, York, UK	- This work aims to contribute to the development and application of UAV for avian surveys.	- UAV survey and analysis approach provided accurate counts (when comparing manual vs. semi-automated counts taken from the UAV imagery) of a wild seabird population with minimal disturbance.
Waite et al., 2019	[32]	A view from above: Unmanned aerial vehicles (UAVs) provide a new tool for assessing liana infestation in tropical forest canopies	University of Nottingham, Nottingham, UK	- To examine the applicability of UAV-derived image data to assess the presence and degree of liana infestation in tropical tree canopies.	- UAV image data of tree canopies can be easily captured and used to assess liana infestation at least as accurately as traditional ground data. The method promotes reproducibility of results, quality control and enables additional variables to be derived.
Colefax et al., 2018	[33]	The potential for unmanned aerial vehicles (UAVs) to conduct marine fauna surveys in place of manned aircraft	National Marine Science Centre, Australia	- To use published literature to contrast marine UAV and manned aerial survey approaches and compare benefits and limitations through sampling efficiency and errors that affect data reliability, particularly for fauna at sea.	- UAVs and associated methodologies can remove much of the observer bias and can improve on perception biases encountered. Empirical testing of UAVs, and associated technologies aimed at increasing sampling and post-processing efficiencies, enable UAVs to fill a niche of delivering efficient and reliable marine aerial survey data on smaller spatial scales.
Hodgson et al., 2016	[34]	Precision wildlife monitoring using unmanned aerial vehicles	Monash University, Australia	- To compare the precision of concurrent UAV-derived image and ground-based counts by for colonies of three seabird taxa in tropical and polar environments.	- The increased count precision afforded by UAVs, along with their ability to survey hard-to-reach populations and places, will likely drive many wildlife monitoring

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					projects, that rely on population counts, to transition from traditional methods to UAV technology.
Yaney-Keller et al., 2021	[35]	Comparison of UAV and boat surveys for detecting changes in breeding population dynamics of sea turtles	Monash University, Australia	- To understand how survey technique and stage of the breeding season might influence the ability to detect turtles using a boat and unmanned aerial vehicle (UAV).	- Overall, it was found that UAVs are an effective tool for studying important, but difficult to observe, aspects of sea turtle biology.
Edney and Wood, 2020	[36]	Applications of digital imaging and analysis in seabird monitoring and research	University of Gloucestershire, Cheltenham, UK	- To summarize the main technologies available for collecting digital data on seabird populations and offer a critical assessment of each data collection method.	- The extent to which digital imaging methods are incorporated into seabird monitoring over the coming years will depend largely on advances in automated image analysis.
Kiszka et al., 2016	[37]	Using unmanned aerial vehicles (UAVs) to investigate shark and ray densities in a shallow coral lagoon	Florida International University, USA	- To use a small UAV for estimating reef shark and ray densities in shallow coral reef habitats, and gain insights into the possible effects of provisioning on elasmobranch spatial distribution (including microhabitat preferences) and densities.	- UAVs can be used to quantify densities of actively swimming elasmobranch species in coral reef habitats at a relatively low cost and over short time periods. They can also be coupled with in-situ measurements.
Sweeney et al., 2016	[38]	Flying beneath the clouds at the edge of the world: using a hexacopter to supplement abundance surveys of Steller sea lions (<i>Eumetopias jubatus</i>) in Alaska	National Marine Mammal Laboratory, Alaska, USA	- To mitigate the challenges faced during traditional aircraft by using UAVs to fill in the gaps of missing abundance information. - To test how adequately the imagery payload could be used to capture aerial images of permanently marked individuals for long-term life history studies.	- Implementation of UAVs was successful, with images collected allowing for the study to identify alpha-numeric permanent marks on individuals as small as juveniles.
Casella et al., 2017	[39]	Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques	Leibniz Center for Tropical Marine Ecology, Bremen, Germany	- To present the results of a survey of a shallow-water reef lagoon environment using a consumer-grade drone.	- Consumer-grade drones can be effectively applied in the monitoring of coral reefs at scales that lie between the typical scales of SCUBA or snorkelling surveys and those typical of air-borne or satellite mapping.
Li et al., 2021	[40]	Leveraging the UAV to support Chinese Antarctic expeditions: a new perspective	State Key Laboratory of Remote Sensing Science, Beijing, China	- To briefly summarise the trend of UAV applications in Chinese and international Antarctic research expeditions.	- The UAV is a valuable supplement to the existing logistical infrastructure. Systematic cooperation of equipment could further promote the capability of polar exploration and support scientific research.
Smith et al., 2016	[41]	Assessment of known impacts of unmanned aerial systems (UAS) on marine mammals: data gaps and recommendations for researchers in the United States	Ocean Associates Inc., Arlington, USA	- To briefly describe commonly used UAVs, provide an overview of published studies that include known effects of UAVs flown in proximity to marine mammals, and present an analysis of information gaps.	- Information is needed to help address UAV disturbance. Researchers can assist by collecting, analysing, and disseminating data about UAV impacts to provide the foundation for sound management strategies, and help agencies realize the full potential of UAV to assist efforts to protect and conserve living marine resources.

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Goebel et al., 2015	[42]	A small unmanned aerial system for estimating abundance and size of Antarctic predators	Antarctic Ecosystem Research Division, La Jolla, USA	- To describe the lessons learned in the development and deployment of small UAVs for use in remote field settings.	- For wildlife census applications where portability, limited take-off and landing distances, flight stability, hovering capability, and quiet operation around easily disturbed wildlife are important, the UAV described and used in this study is exceptional. The relatively low cost is an additional attribute that makes UAVs appealing for wildlife census applications.
Yang et al., 2022	[43]	UAV remote sensing applications in marine monitoring: Knowledge visualization and review	Beibu Gulf University, Qinzhou, China	- To detail the knowledge evolution and progress of the application of UAV remote sensing in marine monitoring.	- The article provides a bibliometric and visual analysis of articles related to marine research with UAVs published from 1993 to early 2022 and then provides an overview of the application of UAV remote sensing technology in marine monitoring. This is with a view to help readers gain a clearer understanding of the development, applications, and challenges faced by the technology.
Durban et al., 2016	[44]	Photogrammetry of blue whales with an unmanned hexacopter	Southwest Fisheries Science Center, La Jolla, USA	- To carry out UAV photogrammetric measures of individual growth and body condition of blue whales to inform about population status and enable assessment of individual health.	- The data collected demonstrates the potential for obtaining repeated estimates of length and width to monitor changes in growth and body condition of blue whales over time, using UAVs, and this utility should also extend to other whale species.
Durban et al., 2015	[45]	Photogrammetry of killer whales using a small hexacopter launched at sea	Southwest Fisheries Science Center, La Jolla, USA	- A report on a recent project using a small UAV as an alternative method for successfully obtaining photogrammetry images of killer whales (<i>Orcinus orca</i>) at sea.	- Can obtain high-resolution images that are sharp enough to differentiate individual whales using natural markings, with precise altitude values to enable quantitative measurements.
Sardà-Palomera et al., 2012	[46]	Fine-scale bird monitoring from light unmanned aircraft systems	Centre Tecnologic Forestal de Catalunya, Catalonia, Spain	- To report on the use of a small UAV to monitor temporal changes in breeding population size in a Black-headed Gull <i>Chroicocephalus ridibundus</i> colony.	- This study showed that UAVs can be used for accurate, repeated, censuses of a breeding colony at minimum cost with minimal colony disturbance.
Rieucou et al., 2018	[47]	Using unmanned aerial vehicle (UAV) surveys and image analysis in the study of large surface-associated marine species: a case study on reef sharks <i>Carcharhinus melanopterus</i> shoaling behaviour	Florida International University, North Miami, USA	- To present a novel, low-cost, quantification technique based on image analysis to detect and locate large epipelagic organisms in shallow water systems and to rapidly quantify fine-scale behaviours observed during UAV video surveys.	- The study demonstrates the potential of a method based on image analysis and using UAV surveys to detect differences in shoaling patterns and swimming dynamics of surface-associated marine organisms.
Borowicz et al., 2018	[48]	Multi-modal survey of Adélie penguin mega-colonies reveals the Danger Islands as a seabird hotspot	Stony Brook University, Stony Brook, USA	- To document a novel multi-modal survey comprised of ground surveys and imagery from both satellites and UAV photographic surveys.	- Results validate the use of Landsat medium-resolution satellite imagery for the detection of new or unknown penguin colonies and highlight the utility of combining satellite imagery with ground and UAV surveys.

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Gooday et al., 2018	[49]	An assessment of thermal-image acquisition with an unmanned aerial vehicle (UAV) for direct counts of coastal marine mammals ashore	University of Canterbury, Christchurch, New Zealand	- To assess the detectability of marine mammals in forested habitat through canopy cover and through ground counts at different times of the day. This is to guide future directions and applications of infrared use in terrestrial population sampling of coastal marine mammals.	- The pairing of UAVs and thermal imagery show great potential in providing a cost-effective method for surveying various habitats.
Žydelis et al., 2019	[50]	Comparison of digital video surveys with visual aerial surveys for bird monitoring at sea	DHI Water Environment Health, Hørsholm, Denmark	- To improve existing knowledge about the advantages and possible disadvantages of digital video techniques for monitoring marine birds at sea.	- Digital video survey techniques are more advantageous than visual aerial surveys for all aspects examined when comparing the results of simultaneous survey flights.
Hodgson and Koh, 2016	[51]	Best practice for minimising unmanned aerial vehicle disturbance to wildlife in biological field research	The University of Adelaide, Australia	- To develop a code of best practice in the use of UAVs to mitigate or alleviate undesirable and unforeseen risks to wildlife.	- Promoting the awareness, development, and uptake of a code of best practice in the use of UAVs will improve suitability as a low impact ecological survey tool. This code is a first, and guiding, step in the development of species-specific protocols that mitigate or alleviate potential disturbance to wildlife.
Geoghegan et al., 2018	[53]	Virological sampling of inaccessible wildlife with drones	Macquarie University, Sydney, Australia	- To show how UAVs can be used to sample viruses.	- The study shows that UAV-based virological surveys of previously inaccessible wildlife populations. Surveys have the potential to help reveal the diversity of the virosphere, facilitate the detection of viruses infecting wildlife and aid evaluation of a creature's pathogenic and zoonotic potential.
Christiansen et al., 2016	[54]	Noise levels of multi-rotor unmanned aerial vehicles with implications for potential underwater impacts on marine mammals	Murdoch University, Murdoch, Australia	- To show that the underwater noise levels produced by two UAVs were lower than or close to ambient noise levels and below the hearing thresholds of most marine mammals.	- This study provides valuable information about the potential impacts of UAVs on the targeted animals. This information will be useful for wildlife managers and regulators when issuing permits and setting guidelines for UAV operations.
Pomeroy et al., 2015	[55]	Assessing use of and reaction to unmanned aerial systems in gray and harbor seals during breeding and molt in the UK	University of St Andrews, St. Andrews, UK	- To examine the utility of UAV systems in determining counts, group composition, providing images of sufficient clarity for photoID, and obtaining data on the responses of animals to these novel stimuli.	- UAVs offer new wildlife data collection opportunities but one of the challenges for users is to optimize the trade-off between required data quality, flying platform performance, imaging payload, and minimal animal response.
Zink et al., 2023	[56]	Assessing the potential disturbance effects on the use of Unmanned Aircraft Systems (UASs) for European vultures research: a review and	University of Veterinary Medicine Vienna, Vienna, Austria	- To assess the potential effects of UAVs and provide practical recommendations for their use in vulture conservation and research.	- The disturbance potential of UAV use is still poorly understood and requires further investigation. Common guidelines, as well as applicable national, regional, or conservation regulations and requirements for UAV operations, must always be observed and missions should always be justified and approved by

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		conservation recommendations			ethical committees with sound scientific and conservation reasoning.
Verfuss et al., 2019	[57]	A review of unmanned vehicles for the detection and monitoring of marine fauna	SMRU Consulting, St Andrews, UK	- To highlight which type of UAV would be suitable for population, mitigation, and/or focal animal monitoring.	- UAVs provide a safe and effective alternative to placing humans within a dangerous working area. Many UAVs are now commercially available, often with fully integrated sensor packages suitable for monitoring marine animals.
Fiori et al., 2017	[58]	The use of unmanned aerial systems in marine mammal research	Auckland University of Technology, Auckland, New Zealand	- To present a general overview of three UAV classes that have been used for marine mammal surveys and the relevant literature.	- UAVs allow researchers to eliminate the research boat bias and can be an invaluable survey tool for shore-based observers, especially when a land vantage point is not available.
Rees et al., 2018	[59]	The potential of unmanned aerial systems for sea turtle research and conservation: a review and future directions	University of Exeter, Cornwall, UK	- To review the potential advances that the use of small, low-cost, UAVs may provide over existing sea turtle research methods.	- UAVs provide an exciting opportunity to enhance our study and protection of sea turtles, provided their benefits, limitations and uses are well understood.
Zu and Li, 2011	[60]	Thermodynamic analysis on energy densities of batteries	Chinese Academy of Sciences, Beijing, China	- To analyse the performance of battery development in terms of energy density, possible energy storage mechanisms and a theoretical thermodynamic calculation on the energy densities of possible batteries.	- Due to the great demand for applications of electric vehicles and stationary batteries there has been an increase in battery energy densities and cyclic performance. Improvements have also been noted to the recycling technologies for rechargeable lithium batteries.
Galkin et al., 2019	[61]	UAVs as mobile infrastructure: addressing battery lifetime	Trinity College Dublin, Dublin, Ireland	- To explore several approaches for a network operator to address the UAV battery lifetime issue and design a UAV network that enables continuous wireless coverage.	- UAV swapping can provide continuous coverage of hotspots but has the drawback of requiring backup UAVs. Solar power can extend the operating time of UAVs, but currently does not appear capable of ensuring continuous flight.
Lee et al., 2015	[62]	Autonomous battery swapping system for quadcopter	Singapore Polytechnics, Singapore	- To present an automated battery swapping system for quadcopters which includes the design concept of the battery swapping mechanisms and the precise landing control with test results.	- The designed prototype can host and swap 3 fully charged batteries and 1 depleted one with the current carousel and arm structure. Future work will be focused on improving the robustness of the entire battery swapping system.
Mangewa et al., 2019	[63]	Integrating UAV Technology in an Ecological Monitoring System for Community Wildlife Management Areas in Tanzania	Nelson Mandela African Institution of Science and Technology, Tanzania	- To explore the achievements, challenges, and gaps in UAV application for wildlife conservation and management.	- The use of UAV technology is becoming increasingly popular for various civilian applications. If well experimented at the spatiotemporal scale for generating diverse ecological data for more than one species of medium-to-large mammals found in groups or individually in mixed habitats, it can become a much more reliable tool.
Hardin & Jensen, 2011	[64]	Small-Scale Unmanned Aerial Vehicles in	Brigham Young University, USA	- To provide a perspective to focus the research and development community on the pressing needs for innovation in hardware, software, and methodology to	- The promise represented by small-scale aerial vehicles for environmental research nearly three decades ago remains unfulfilled. The challenges to fulfilment are

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		Environmental Remote Sensing: Challenges and Opportunities		improve the competency of small-scale unmanned aerial systems to gather high-quality environmental imagery.	formidable, and many will require the use of technologies that are now only experimental.
Hodgson et al., 2013	[65]	Unmanned Aerial Vehicles (UAVs) for Surveying Marine Fauna: A Dugong Case Study	Murdoch University, Australia	- To determine the capabilities of UAVs for fauna surveys.	- There are several potential advantages to using the UAV to conduct surveys rather than a manned aircraft.
Ortega-Terol et al., 2017	[66]	Automatic Hotspot and Sun Glint Detection in UAV Multispectral Images	University of Salamanca, Spain	- To describe the algorithms developed to deal with sun glint and hotspots and its integration in a UAV flight planning and control software developed by the authors.	- The process developed allows to solve the problem from a twofold perspective: from its possible prevention during flight planning to its detection once the flight was executed applying a flight control protocol, especially for those situations in which is mandatory to fly during the hours where the sun reaches its maximum height, being inevitable that these defects can appear.