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FEATURED PAPER

Use of Drones in Fishery Science

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Abstract
The use of unmanned aircraft systems (UASs), commonly referred to as drones, has rapidly expanded across many scientific disciplines. Like other fields, fisheries research would benefit significantly from broader use of this emerging technology but has lagged behind other disciplines. Like the implementation of satellite and aircraft-based remote sensing technology in previous decades brought a greater understanding of large-scale spatial patterns and processes, UAS technology has the potential to put those tools in the hands of individual researchers, allowing implementation at finer spatial and temporal scales for a fraction of the cost. Our goal is to provide a "how-to" for fisheries researchers interested in using UAS technology. We outline the necessary steps for any UAS project from choosing the appropriate platform and sensors to data acquisition and analysis. We also present the current ways in which UASs are being used in a fisheries research context as well as potential future research directions.

Recently, the use of unmanned aircraft systems (UASs) has rapidly increased across many scientific disciplines. From the highly applied (agriculture and inspections) to the most basic research (ecology and geology), UASs offer a unique opportunity for data collection that was either very costly or impossible previously. However, while the prospect of high-frequency, high-quality, low-cost data is appealing, determining the right UAS platform, sensors, and data processing pipeline can create a high barrier to entry for many researchers interested in using UASs as a tool in their research. Our goal is to provide an introduction to implementing UAS technology in a fisheries research context. Since UAS technology is rapidly evolving, we will focus less on specific technologies and more on the general capabilities of UAS platforms, data acquisition and workflows, and current and potential applications to fisheries research.

One of the most significant advancements in UAS technology in recent years is the automation of flight controls and flight planning in nearly every mid- to high-end UAS platform available today. The levels of automation and flight stability currently available allow researchers to deploy remote sensing equipment that has traditionally been limited to satellites and larger aircraft (Pajares 2015). Multispectral photography, thermal imagery, light detection and ranging (LIDAR), and many other sensors can now be deployed using UASs with higher resolution and lower costs than ever before (Chust et al. 2008; Yang and Artigas 2010; Klemas 2015; Yahyanejad and Rinner 2015). As the platforms and sensors have become less

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expensive and easier to use, the primary bottleneck has become the processing and analysis of UAS data. In fact, data processing is often the costliest and most time-consuming aspect of any UAS project. Therefore, it is critical to thoroughly plan a UAS project so that the final deliverables meet the objectives of the research questions and drive the platform choice and analytical process so as to ensure project success.

Currently, UASs in fisheries research are used for two primary purposes: (1) to delineate habitats and provide high-quality evaluations and (2) to catalog the occurrence of species or individuals (Kopaska 2014). Both coastal and lotic environments have seen increased use of UAS technology to identify and map critical habitat, including tidal wetlands (Kalacska et al. 2017), fish nursery grounds (Ventura et al. 2016), inlet topography (Long et al. 2016), coastline mapping (Mancini et al. 2013; Darwin et al. 2014; Turner et al. 2016), channel morphology (Casado et al. 2015; Tamminga et al. 2015), river bathymetry (Zinke and Flener 2013), restoration monitoring (Cress et al. 2015), and physical habitat assessments (Hentz et al. 2018). These data streams can then be used for any number of important management tasks from identification of critical nursery habitat to determining sites for remediation and removal of invasive species. For example, researchers in Texas covered over 60 km along a river with a fixed-wing UAS to identify pools for removal of nonnative Smallmouth Bass *Micropterus dolomieu* (Hardy et al. 2012). Researchers also assessed cumulative changes in instream habitat for native Guadalupe Bass *Micropterus treculii* (Birdsong et al. 2015). Kalacska et al. (2018) combined aerial imagery and underwater photography to quantify fish habitat complexity. Using a method called fluid lensing technology, they created three-dimensional (3D) imaging of aquatic ecosystems from centimeter-scale habitat data through a wave distortion smoothing algorithm (Chirayath and Earle 2016). Using thermal imaging, researchers were able to identify areas with groundwater input, which enabled them to map potential salmon and steelhead *Oncorhynchus mykiss* summer refuge habitat (Willms and Whitworth 2016).

The second primary use of UASs in fisheries research is the identification of individuals and species for abundance and telemetry information. Currently, the majority of this work is done on epipelagic megafauna (e.g., whales and sharks). In these situations, the primary advantage of UASs is the area covered and the field of view (FOV; Durban et al. 2015; Hodgson et al. 2016; Kiszka et al. 2016). Outside of megafauna studies, the literature for fisheries population assessments is currently limited, despite the fact that such surveys would be possible, particularly in clear coastal waters or stream ecosystems. Tyler et al. (2018) described perspectives for collecting freshwater fisheries census data with Taimen *Hucho taimen* surveys in Mongolia to test the feasibility of species identification (without animal disturbance), size and detection rate estimates, and automated fish recognition. Spawning surveys for Chum Salmon *O. keta* and Sockeye Salmon *O. nerka* have been successfully conducted (Kudo et al. 2012; Whitehead et al. 2014). One study found UAS image counts to be more accurate than manned helicopter flights for the enumeration of Chinook Salmon *O. tshawytscha* redds (Groves et al. 2016). A novel approach for schooling fish was to combine acoustic data with UAS aerial imagery to estimate Atlantic Bluefin Tuna *Thunnus thynnus* biomass and aggregation behavior (Vanderlaan et al. 2014; Figure 1).

Although there has been a number of successful implementations of UAS technology to fisheries research questions, the field still lags others in the implementation of this new and powerful tool. What follows is a “how-to” for fisheries researchers to begin implementing UAS technology in their research as well as some potential ideas for new and innovative ways of applying this technology to fisheries issues.

EQUIPMENT AND APPLICATION

There are two primary UAS platforms in use today: multi-rotor and fixed wing. The type of platform to select depends primarily on the area to be surveyed. Regardless of the type, a typical commercial off-the-shelf UAS platform will cost between US$500 and $50,000 (typically less than $10,000) and will come equipped with a high-quality RGB color camera (typically 4K ultra-high definition), onboard GPS, and a touchscreen interface with flight planning software installed (Colomina and Molina 2014). A wide array of additional sensors can be integrated with the existing platform and also often come with easy-to-use software (Anderson and Gaston 2013; Christie et al. 2016). Any UAS can produce significantly better spatial resolutions than those obtained from satellites or manned aircrafts with user-determined revisit periods and can be simultaneously tested against ground-based surveys. In this quick overview, we focus on battery-powered, small UASs (sUASs; <25 kg [<55 lb]) because these safe and affordable systems exhibit tremendous potential to produce low-altitude, high-resolution data pertinent to a variety of fisheries science applications. They are also regulated in the USA by the Federal Aviation Administration (FAA) under the Small Unmanned Aircraft Systems Rule, commonly known as Part 107 (sUAS Part 107; FAA 2016), which allows commercial and scientific operations of small UASs < 25 kg.

There is no single UAS that can accomplish all of the objectives for all users. Each project objective must drive the decision on the best UAS platform considering specific project goals and budgetary constraints. There is a

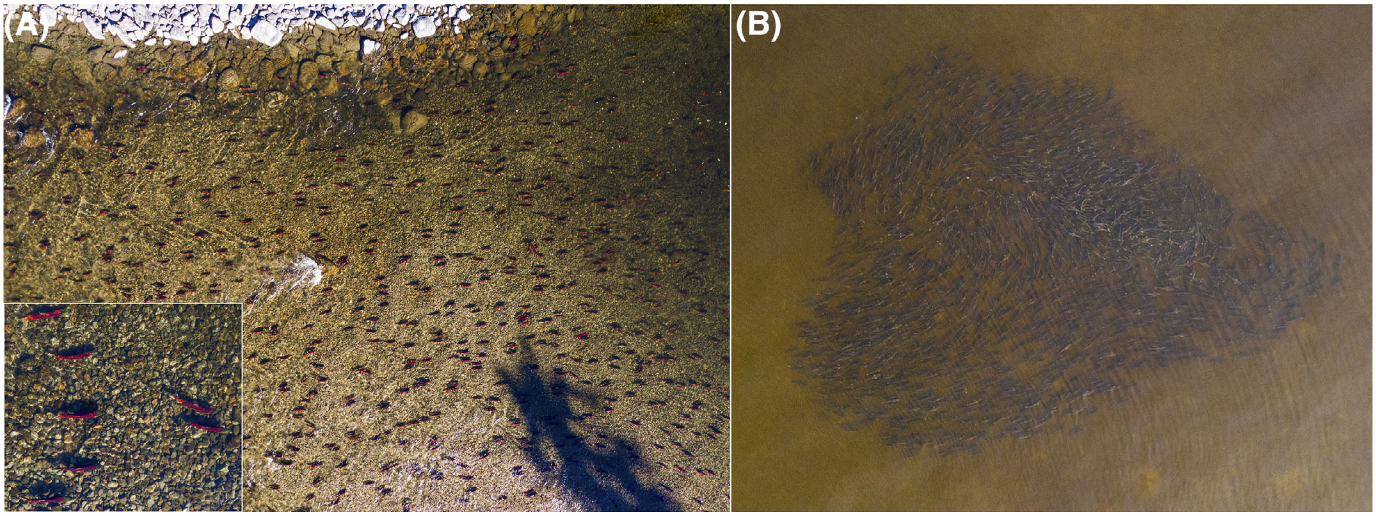

FIGURE 1. Unmanned aircraft system images of **(A)** Sockeye Salmon in Alaska and **(B)** Red Drum *Sciaenops ocellatus* in Florida (Photographer: Jared Zissu).

multitude of UAS platforms spanning customizable kit systems to flight-ready, off-the-shelf models. The variety of platforms has rapidly increased and the costs have fallen for most types of UASs, making the barrier to entry lower than it has been in the past. Generally speaking, first-time users should strongly consider purchasing the smallest and cheapest UAS that will fulfill their project requirements to ease operational and budgetary concerns (Joyce et al., in press). See Watts et al. (2012), Klemas (2015), Pajares (2015), and Padua et al. (2017) for more details on aircraft types and capabilities.

The first step in choosing the right platform is to determine whether a multi-rotor or fixed-wing UAS is more appropriate for your application. We outline a number of distinctions below, but the primary difference between rotor and fixed-wing UASs is the areal coverage they can provide. Multi-rotor platforms are better for smaller areal extents (tens of hectares per day), while fixed-wing vehicles have longer flight times and cover larger regions (hundreds of hectares per day). All things considered, an off-the-shelf multi-rotor is the simplest and least expensive option for most small projects. Automated mission planning for multi-rotor vehicles allows pilots to set flight parameters and eliminates the need for manual control from lift-off through landing. Some basic products come equipped with cameras and offer little to no potential for sensor exchange, while other models are designed for customization and swappable payloads. It should be noted that the aircraft itself does not always comprise the bulk of costs associated with UASs. Most often, the majority of expenses for deploying a UAS platform come from peripheral costs, which can include upgraded cameras, batteries, propellers, chargers, a tablet/smartphone for controls, a weatherproof hard case, FAA certification fees, processing software, and file storage devices. This means that total costs can vary substantially between platforms. For example, marine researchers used the custom-made APH-22 hexacopter (~$35,000) for leopard seal *Hydrurga leptonyx* photogrammetry, while others analyzed fine-scale movement patterns of sharks with an off-the-shelf DJI Phantom 3 Professional (~$900; Krause et al. 2017; Raoult et al. 2018). It remains a user decision to determine the best UAS platform and sensor options based on operational and budgetary constraints.

Multi-Rotor Platform

Multi-rotor UASs are best suited for small-scale projects or where the areas are constrained, where takeoff and landing locations are difficult to navigate, and where ease of use is important. They have vertical takeoff and landing ability and can hover and change altitude to achieve desired imagery resolution. Multi-rotor units are also better at maneuvering than their fixed-wing counterparts. The typical rotor configurations are quad-, hexa-, and octo-"copter" types propelled by four, six, and eight fixed-pitch blades arranged around a main central body. The quadcopter is a popular and simple layout that offers stability and reliability from four rotors (Figure 2). Additional rotors can increase stability and wind resistance but also may reduce the risk of crashing; for example, some octocopters can remain in the air if one rotor loses power. Average battery life is typically 20–40 min. Extra weight decreases flight time and payload capacity remains potentially limiting, with most multi-rotor UASs being unable to handle over 2 kg while maintaining reliable flight capabilities and battery life. Flights can be manually controlled or automated using mission planning software. Built-in accelerometers and internal GPS devices have made multi-

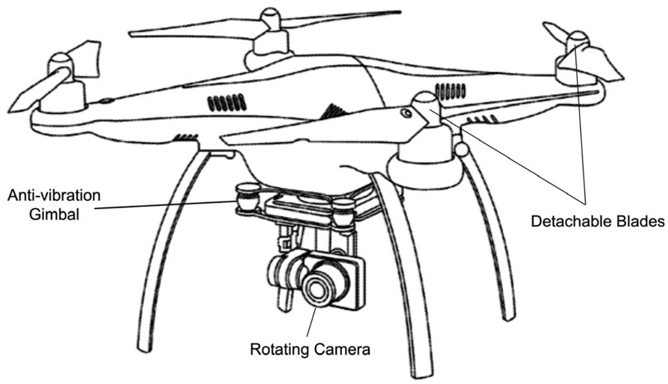

FIGURE 2. Example schematic of a lightweight quadcopter.

rotors remarkably stable, precise, and responsive platforms. Chief advantages are maneuverability, the ability to vertically take-off and land without a flat surface (by hand), and the capacity to hover; the weaknesses of the multi-rotor unit are its short flight time and range (González-Jorge et al. 2017).

Rieucau et al. (2018) conducted UAS flights using a DJI Phantom II quadcopter and a GoPro Hero 3+ with a polarizing filter to study shoaling pattern behavior of Blacktip Reef Sharks *Carcharhinus melanopterus* in a shallow lagoon environment. Four-hundred-meter transects were flown at an altitude of 12 m perpendicular to a fringing reef, a deeper channel, and a back reef sandflat to obtain images of Blacktip Reef Shark aggregations. One representative frame by habitat per flight was selected to avoid replication analysis of images of the same aggregation, and a semi-automated tracking algorithm was applied to quantify shoaling tendency using size estimates, distance between individuals, and swimming alignment. Results showed that Blacktip Reef Sharks exhibited greater alignment in the shallow reef habitat than in the deeper channel. It is necessary to enhance our abilities to interpret animal responses to changing ecosystems, but obtaining social and behavioral information on free-ranging aquatic organisms is often difficult without some level of disturbance. This study demonstrates the potential for quantifying swimming dynamics and fine-scale movement patterns in marine organisms by using noninvasive, low-cost UAS technology.

Fixed-Wing Platform

Fixed-wing platforms can cover larger areas than multi-rotor vehicles and are designed for greater ranges and longer flight durations. They can typically reach distances upwards of 25 km (current maximum = 40 km) from the launch site, but under current FAA regulations, they must remain within the visual-line-of-sight (VLOS) of the pilot. Fixed-wing vehicles are generally larger than multi-rotor systems (wingspans ~1–3 m) and require more substantial takeoff and landing surfaces; in most cases, launching and landing are accomplished manually (Anderson and Gaston 2013). Initial propulsion can be created with manual, bungee, or mechanical power, and landing is achieved through a slow, controlled glide onto flat, favorable ground. Some hybrid models exist that allow for vertical takeoff and landing (e.g., BirdsEyeView Aerobotics FireFLY6 Pro). Navigation can be accomplished manually or flight missions can be loaded for the aircraft to autonomously survey a preprogrammed area.

Broussard et al. (2018) used a fixed-wing Trimble UX5 Aerial Rover (Figure 3) to collect aerial imagery of a coastal marsh, and they compared UAS data to WorldView-2 and WorldView-3 satellite-based calculations for land–water interface, dominant vegetation types, normalized difference vegetation index (NDVI), elevation, and other landscape metrics. The project site (0.725 km^2 [~180 acres]) was a degraded marsh consisting primarily of saltmeadow cordgrass *Spartina patens* along with common reed *Phragmites australis* and a mixture of other species. The most significant differences between the satellite and the higher-resolution UAS-based imagery were seen in vegetation and land/water classifications where the high-resolution imagery (~2.54-cm resolution pixels in this case) was used to develop land–water maps and habitat fragmentation indices that were more accurate and representative of the degraded marsh landscape. The Broussard et al. (2018) study provides evidence that UAS data can provide rapid, site-specific assessments of wetland condition and marsh fragmentation to better inform resource managers for habitat restoration decisions. Especially when scaled up and considered within the broader context of satellite-based, regional-level information, these methods provide many advantages over traditional techniques to quantify ecosystem services, monitor disturbance response, and analyze landscape change over time.

Sensors

Sensory equipment has rapidly improved along with UAS technology, leading to higher-quality, lower-cost, and miniaturized products (Cress et al. 2015). The majority of projects can be completed by using the camera that is included with the aircraft. Most off-the-shelf UASs now come with a good-quality RGB camera that is capable of producing high-resolution pictures and video sufficient for imagery interpretation or photogrammetry. Most of the multi-rotor UASs that are popular among consumers can handle light additional payload with capacities around 0.5–1.0 kg; however, models equipped with integrated cameras are not typically designed to carry additional payloads and therefore require customized integration kits. Third-party kits are rapidly evolving to work around this problem, allowing users to mount additional sensors along with the integrated camera.

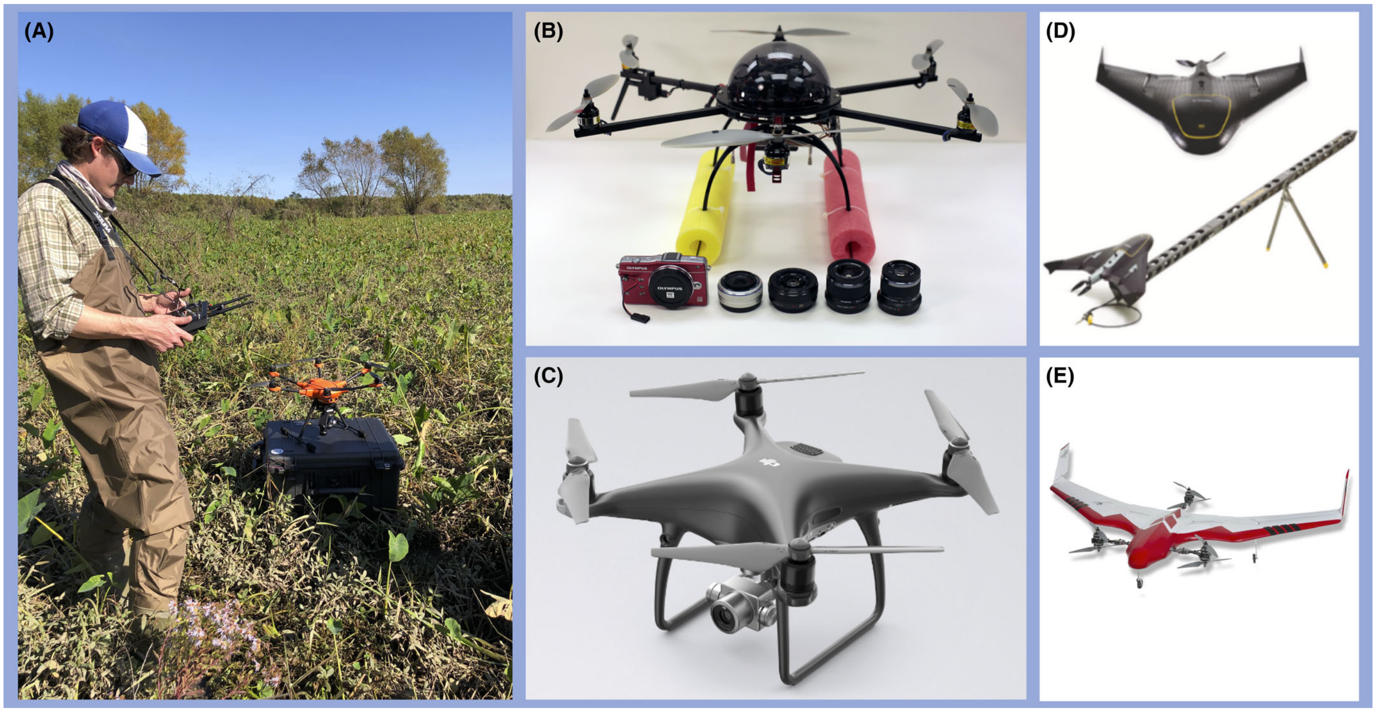

FIGURE 3. Current examples of small unmanned aircraft systems: **(A)** Yuneec H520, **(B)** Aerial Imaging Solutions APH-22, **(C)** DJI Phantom 4 Professional, **(D)** Trimble UX5, and **(E)** BirdsEyeView Aerobotics FireFLY6 PRO (images sourced from author and manufacturer Web sites).

The variety of compact, UAS-ready sensors has expanded significantly in the last 5 years, including multispectral, hyperspectral, synthetic aperture radar, thermal, LIDAR, and other types. Although multispectral information is widely used in forestry and precision agriculture to assess vegetation health (e.g., NDVI) and to aid in classification/mapping, aquatic applications are limited (Boon and Tesfamichael 2017; Díaz-Delgado et al. 2018). Compact forward-looking infrared thermal cameras mounted on UAS platforms have been used for mammal and bird inventory, poaching, fire detection, disaster response, surveillance and security, temperature and effluent mapping, and much more. The infrared wavelength is used differently (e.g., far versus near region) for various sensory technologies, and its use can affect the camera's limitations and cost. Infrared thermal imaging systems are generally more expensive than infrared night vision, for example. Multispectral and thermal camera resolutions are typically lower than true color imagery and require additional calibration and postprocessing analysis (Chabot and Bird 2015). For more comprehensive information regarding sensors, see Hardin et al. (2019).

Data Acquisition

Detail on best practices for collecting quality data from UASs was effectively described by Gonçalves and Henriques (2015), Jensen (2017), and Joyce et al. (in press). Procedures may vary based on aircraft, sensor, location, and desired end-product, but common methods are similar (Figure 4). Mapping data generally require specific parameters for altitude, solar positioning, air speed, and image overlap (e.g., 75% front-lap and side-lap). Sensor and software user manuals can provide survey specifications. Ground control points (GCPs), used in conjunction with onboard GPSs and a differential GPS, improve the accuracy of georeferenced data by creating tie points for coordinate reference systems. The placement and configuration of GCPs can be time consuming but drastically increase precision for scaling and calculations (Bryson et al. 2013). Aerial visualization of study sites can be easily accomplished with much fewer requirements. It is important, however, to understand the camera's FOV to achieve appropriate survey coverage based on altitude and camera type. In some cases, FOV and flight coverage must be estimated manually, but many flights now rely on autonomy for optimal sampling procedures.

Mission planning software makes conducting a flight very simple and significantly reduces the chance of pilot error. Programs overlay grid or polygon areas on satellite imagery and cover the zone through predetermined transects or by visiting waypoints. Users can define the shape of the survey area with a polygon tool, and the program calculates flight time and number of batteries needed based on altitude, image overlap, and speed. Not all systems have this capability, but there are several options that allow researchers to apply this planning to their

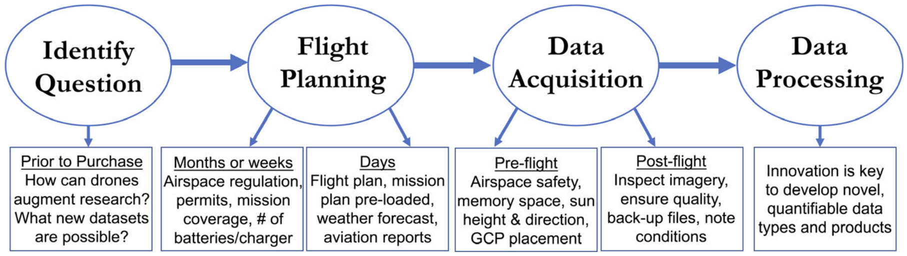

FIGURE 4. Example of workflow and time frame for unmanned aircraft system data collection (GCP = ground control point).

flights. After uploading the mission plan, no additional in-flight communication is needed from takeoff to landing. Although many situations require manual piloting, software has made conducting a fully automated or semi-automated flight fast and uncomplicated. Automation greatly reduces accidents caused by pilot error but can create issues with animal detection (e.g., double-counting), and communication link loss or auto-return failure may result in fatal crashes or submersion.

Data Processing

Data postprocessing is currently the most time consuming and potentially costly aspect of any UAS project. Analytic pipelines and packages are rapidly developing and allow users nearly limitless opportunities to create new data-driven products beyond simple image or video analysis. Modern motion-stabilization in aircrafts and advances in software and image processing algorithms have simplified and accelerated the production of maps and other data sets. Structure-from-motion photogrammetry can produce very high-resolution geolocated 3D maps that are useful for identification and characterization of aquatic habitats through powerful techniques, such as object-based image analysis, which incorporates shape, size, texture, and context in classification protocols. These processes involve stitching overlapping geotagged images together to create uniformly scaled orthomosaics, digital surface models (Figure 5), and point clouds. Processing requires the storage of large numbers of data files and is expedited by substantial computing power. High-quality georeferenced images and videos quickly result in large file sizes that easily exceed several gigabytes in a single flight. Licenses for photogrammetry software are expensive, and lifetime subscriptions can often exceed equipment costs; however, several free/open-source options exist. In some instances, postprocessing and flight planning software is proprietary to the manufacturer, and researchers must be aware of specific hardware and software drawbacks.

Recent technological advancements have allowed researchers to expand the range of questions being addressed using UASs—in particular, the development of novel image processing techniques that not only improve the quality of the data but can also be done in a timely manner, allowing for aerial surveys at ever finer scales. Traditionally, aerial surveys using UASs equipped with high-resolution video cameras have been used in studies of marine wildlife to assess their distribution, density, and abundance (Hodgson et al. 2016; Kiszka et al. 2016; Rieucau et al. 2018), with no or limited disturbance (but see Ramos et al. 2018). However, the count data collected through UAS surveys only provide information about how many, when, and where surface-associated wild animals are spotted; these data offer limited to no information about how the organisms react to biotic (e.g., predators, human disturbances, or fisheries activities) or abiotic factors at different temporal and spatial scales. In recent years, a great deal of effort has been directed toward the development of analytic approaches to describe and quantify swimming dynamics, collective behavior, social interactions, and trophic (e.g., predator–prey) interactions of surface-oriented marine species. For example, Rieucau et al. (2018) presented a novel image analysis technique applied to UAS survey data to detect and locate free-ranging epipelagic individuals (Blacktip Reef Sharks) within aggregations in a shallow lagoon off the north coast of Moorea, French Polynesia. Their technique relied on the development of a semi-automated tracking algorithm (see Rieucau et al. 2018: their Figure 3) for detecting and precisely positioning each individual shark swimming in shoals close to the surface. Their approach was also employed to provide (1) relative body size estimates (measured in pixels) and (2) intrinsic characteristics of shark shoals (i.e., distance and alignment among shoalmates) across different environmental conditions. Their study demonstrates how postprocessing procedures based on UAS image analysis can offer unprecedented opportunity to explore fine-scale collective behavior and shoaling patterns of surface-oriented marine animals without having to rely on time-consuming postprocessing procedures.

It is now recognized that such "static" approaches to analyzing UAS survey-based imagery need to be used in concert with automated video postprocessing to accurately depict swimming dynamics of targeted epipelagic aquatic organisms. Automated tracking techniques, such as the use of particle image velocimetry, have been successfully

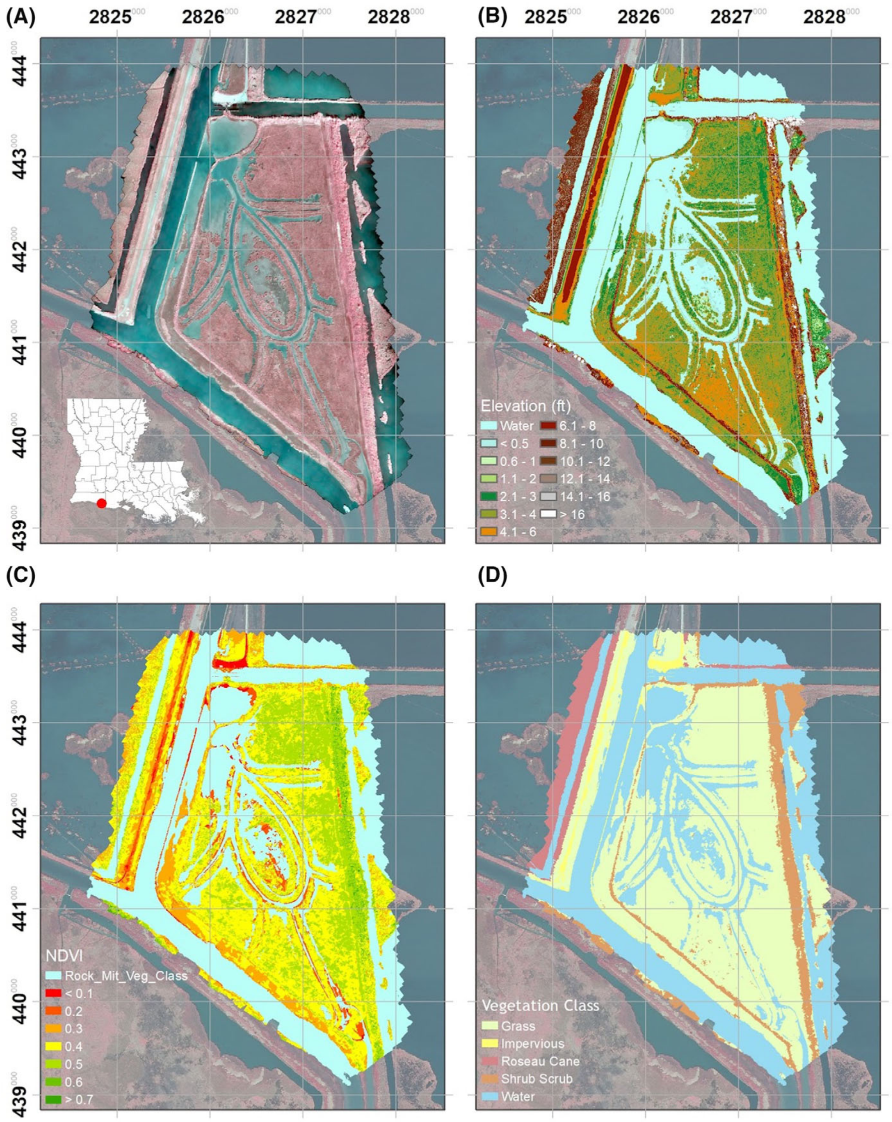

FIGURE 5. Unmanned aircraft system-derived data products at a 0.405-km^2 (100-acre) wetland mitigation bank in Cameron Parish, Louisiana, including **(A)** near-infrared hyperspatial imagery, **(B)** digital surface model with survey-grade elevation values relative to the North American Vertical Datum of 1988 (Geoid09), **(C)** normalized difference vegetation index (NDVI), and **(D)** classified vegetation coverage by dominant species.

employed by researchers to measure collective reactions of pelagic fish (Rieucau et al. 2016a, 2016b). A current challenge for the further development of UAS video analysis resides in the capability to estimate and subtract the UAS's movement. As a possible way to address this issue, Rieucau et al. (2018) proposed to consider UAS motion as discrete image displacements, allowing them to establish reference points, isolate one or several moving objects, and finally remove background movement. Once the UAS's motion has been subtracted, the optic-flow technique would be an efficient means for quantifying the movement of large-bodied individual organisms (i.e., large epipelagic fish or marine mammals), the whole aggregation, and/or the center of mass of shoals containing small-bodied fish, for which video resolution does not allow the identification of individuals.

Access to low-cost UAS survey methods combined with novel postprocessing quantification procedures for fixed images or video footage will allow the study of individual and/or shoaling patterns of commercially and ecologically relevant marine organisms and the monitoring of movements in response to predation, fisheries pressure, or fluctuation in environmental factors. Combined with limited catch data, UAS survey data can be used to develop nonintrusive stock assessment techniques. These data can be used to establish a time-series fisheries database for density estimates, and in some cases, size-class information can be extrapolated.

Regulation

Recent changes in federal regulation have contributed to the boom in use of UASs. Previous expansion was hindered by the regulatory framework, and it was suggested that aviation administrations and laws—rather than technological growth and development—would constitute the limiting factor (Vincent et al. 2015). In August 2016, the FAA adopted sUAS Part 107 (FAA 2016). The regulations changed to allow for civilian sUAS pilot certification without obtaining a regular pilot's license. To fly commercially, pilots must obtain a Remote Pilot Airman Certification by completing a 2-h, 60-question exam (92% pass rate) and must adhere to operating rules (FAA 2018). Scientists are able to obtain research exemptions and permits for site-specific projects through the managing agency and/or the FAA. General commercial operation requirements are as follows: the aircraft must weigh less than 25 kg (55 lb) and must be flown within the VLOS, under an altitude of 120 m (400 ft), during daylight or civil twilight, not directly over people, and within specific airspace regulations (FAA 2016). If the pilot in command cannot fulfill VLOS requirements, a visual observer must also be present for greater situational awareness during a flight. For more information, visit www.faa.gov/uas. Pilots can obtain waivers to certain rules pending FAA approval.

It is imperative that the pilot in command has sufficient training and knowledge of equipment, in-flight procedures, and airspace regulations to ensure safety and professionalism.

Faunal Response Considerations

Unmanned aircraft systems present a minimally invasive means to study animals, but researchers should exercise caution to ensure that they do not become a new source of disturbance for wildlife. Noise and visual cues (e.g., shadows) are the two primary types of disturbance. Response level depends on many factors, including aircraft type and size, flight altitude, and the organism's life stage and present state (e.g., migrating, breeding, feeding, or resting; Smith et al. 2016). Negative reactions to UASs have been documented for birds, reptiles, and mammals (Mulero-Pázmány et al. 2017; Bevan et al. 2018). Marine mammals (specifically cetaceans, sirenians, and pinnipeds) show a broad range of responses to different platforms, approaches, and proximities. Ramos et al. (2018) noted that common bottlenose dolphins *Tursiops truncatus* exhibited mixed responses to UASs at altitudes of 11–30 m, but Antillean manatees *Trichechus manatus manatus* fled from overhead flights ranging from 6 to 104 m. Common bottlenose dolphin behavioral responses were highly variable and brief, and they typically reverted to the preresponse state or changed activities. Antillean manatees, however, displayed strong disturbance responses, fled from the aircraft, and actively evaded if pursued. Many encounters did not elicit a response from either species, but individual and species-specific responsivity necessitates caution and quality documentation of how animals are affected by UASs. Due to the limited understanding of undesirable impacts caused by low-altitude UAS flights, we must strive to reduce the risk of disruption, report positive and negative observational responses, and continue to develop criteria for best possible practices in field research (Hodgson and Koh 2016).

Limitations

New technology inherently comes with new obstacles and challenges. Although now easier to use, UASs are still constrained by many practical limitations. Like other airborne platforms, UAS operations can be significantly impacted by environmental conditions. Flights require fair weather, and many surveys need good sunlight. Moderate cloud cover and humidity degrade image quality and can limit the detection of individuals. Wind strength varies with altitude, and sustained speeds greater than 24.14 km/h (15 mi/h) quickly deplete batteries. Short battery life and flight duration remain issues with many UAS platforms. Additional batteries are usually necessary (especially with multi-rotors), and some projects require a field charging system. The regulation requiring VLOS also significantly restricts survey range. An aircraft's visible distance is unique to daily environmental conditions, the type and size of the vehicle, and an individual pilot's ability to maintain visual contact. A small multi-rotor flies out of eyesight typically between 500 and 900 m, and a mid-sized model does so at around 1–2 km; however, unfavorable weather conditions greatly reduce these distances. Strobe lights can be added as visual aids, but flights are still restricted to daylight/twilight, prohibiting any nocturnal analysis. Airspace regulation is another limiting factor; for example, flights over land controlled by state and federal agencies usually require a special use permit. Pilots must check site-specific regulations several months ahead of time to comply with local laws and procedures.

DISCUSSION

Advances in new technology beckon resource managers and scientists to ask and answer new questions about ecological processes. Unmanned aircraft systems have revolutionized spatial ecology with the arrival of high-resolution data, low operating costs, and repeatability with user-determined survey times (Anderson and Gaston 2013). Platforms, data processing, and analytic tools are easily available to practitioners of any experience level (Ventura et al. 2018). Data that were previously unattainable can now be readily produced with this technology. Although barriers to entry are lower than ever before, the technology does not come without challenges. Burden of regulation, short flight durations, limited payload capacity, and difficulties in processing large data sets all hinder expansion; however, continual improvements in hardware and software are addressing many of these concerns. All things considered, a key part of the process is to identify fundamental questions prior to flights and think about UASs as a true remote sensing tool with the same capabilities of aircraft and commercial satellites—but on a local scale and within reach of almost any researcher.

Modern programs and algorithms create opportunities to process UAS data into unique products. New types of information can be pulled out of flight recordings through object- and pixel-based classification schemes. However, developing these data sets into meaningful, reproducible, and useful products is still an evolving field (Woodget et al. 2017). Based on the evolution of processing methods and future possibilities, postcollection data can be integrated into other frameworks or processed into brand-new data sets. Behavioral analysis and fine-scale movement patterns (Raoult et al. 2018; Rieucau et al. 2018), improved tracking of planktonic food and harmful algal blooms (Kislik et al. 2018), and fluid lensing to see through water and catalog subsurface habitat (Chirayath and Earle 2016) are examples of novel postprocessing techniques that can provide greater insight into critical questions in fisheries research.

Fluid lensing is an experimental algorithm that uses water-transmitting wavelengths to survey underwater objects with UASs and multispectral sensors to create habitat maps and 3D bathymetry models at centimeter-scale spatial accuracy (Chirayath and Earle 2016). The fluid lensing algorithm helps to remove refractive distortions in imagery caused by surface waves and produces a depth estimate for use in combination with the structure-from-motion photogrammetry approach, allowing the creation of 2D and 3D underwater scenes. The technique was applied to coral reef ecosystems and is limited by water clarity, irradiance, and depth (~10 m). Reconstructions allowed for delineation of bleached coral from living coral, fish identification and fish size estimation (~20 cm), and documentation of morphologically distinct stromatolites. This method has the potential to revolutionize monitoring and management of shallow-water environments through rapid, low-cost habitat and species surveys (Chirayath and Earle 2016). Fluid lensing has counterparts in imagery processing for other remote sensing configurations, but many novel processing techniques for UAS data are still in their infancy.

Unmanned aircraft systems provide tremendous opportunities for fisheries managers to improve resource monitoring through real-time survey information (e.g., fishing gear, boat/angler counts, and socioeconomic data) and to combat illegal, unreported, and unregulated fishing (Toonen and Bush, in press). Protected areas would benefit from more observation to preserve biodiversity and uphold conservation goals (López and Mulero-Pázmány 2019). Many nations have incorporated UASs into law enforcement frameworks; although this passive surveillance approach is helpful in documenting unlawful behavior, it can come at the cost of privacy for others (Sandbrook 2015; Howard 2017). Unmanned aircraft systems can also improve monitoring and documentation of cultural fishing practices, thus better preserving artisanal or subsistence tradition and heritage. These methods can also be used globally for determining effort of remote or recreational fisheries.

CONCLUSION

There is great potential for the use of UAS technology in fisheries science. The primary use of UASs and the most beneficial products will be determined by where the technology goes in the next few years and by the efforts of scientists in taking the next steps with the data. Postprocessing analysis is pivotal to further this technology's contribution to the field. Unmanned aircraft systems offer safe and affordable methods to study ecological phenomena at higher resolutions and on spatial and temporal scales that are unattainable with satellites or manned aircrafts. Technological improvements with platforms and automated flight planning combined with modern processing and analytic software present researchers across all disciplines with powerful tools at a low barrier to entry.

Unmanned aircraft systems can help to fill a niche in scientific remote sensing and supply spatial information for wildlife surveys, aquatic habitat maps, water resource and disturbance event monitoring, and socioeconomic analysis. Future developments in sensors, postprocessing software and algorithms, and automation in animal detection will continue to refine procedures and strengthen results. Increased freedom in flight restrictions with regard to VLOS rules would provide greater opportunity for pilots. The FAA maintains that the aircraft must stay close enough to be seen by the operator without the use of visual aid devices other than corrective lenses. Although challenges remain, modern technology and the current regulatory environment have made using UASs a viable option for anyone.

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REFERENCES

Anderson, K., and K. J. Gaston. 2013. Lightweight unmanned aerial vehicles will revolutionize spatial ecology. Frontiers in Ecology and the Environment 11:138–146.

Bevan, E., S. Whiting, T. Tucker, M. Guinea, A. Raith, and R. Douglas. 2018. Measuring behavioral responses of sea turtles, saltwater crocodiles, and crested terns to drone disturbance to define ethical operating thresholds. PLoS ONE [online serial] 13(3):e0194460.

Birdsong, T., M. Bean, T. B. Grabowski, T. B. Hardy, T. Heard, D. Holdstock, K. A. Kollaus, S. Magnelia, and K. Tolman. 2015. Application and utility of a low-cost unmanned aerial system to manage and conserve aquatic resources in four Texas rivers. Journal of the Southeastern Association of Fish and Wildlife Agencies 2:80–85.

Boon, M. A., and S. Tesfamichael. 2017. Wetland vegetation integrity assessment with low altitude multispectral UAV imagery. International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences XLII(2/W6):55–62.

Broussard, W., G. Suir, and J. Visser. 2018. Unmanned aircraft systems (UAS) and satellite imagery collections in a coastal intermediate marsh to determine the land–water interface, vegetation types, and normalized difference vegetation index (NDVI) values. U.S. Army Corps of Engineers, Engineer. Research and Development Center, Wetlands Regulatory Assistance Program, Technical Note WRAP-18-1, Vicksburg, Mississippi.

Bryson, M., M. Johnson-Roberson, R. J. Murphy, and D. Bongiorno. 2013. Kite aerial photography for low-cost, ultra-high spatial resolution multi-spectral mapping of intertidal landscapes. PLoS ONE [online serial] 8(9):e73550.

Casado, M. R., R. B. Gonzalez, T. Kriechbaumer, and A. Veal. 2015. Automated identification of river hydromorphological features using UAV high resolution aerial imagery. Sensors 15:27969–27989.

Chabot, D., and D. M. Bird. 2015. Wildlife research and management methods in the 21st century: where do unmanned aircraft fit in? Journal of Unmanned Vehicle Systems 3:137–155.

Chirayath, V., and S. A. Earle. 2016. Drones that see through waves—preliminary results from airborne fluid lensing for centimetre-scale aquatic conservation. Aquatic Conservation: Marine and Freshwater Ecosystems 26(S2):237–250.

Christie, K. S., S. L. Gilbert, C. L. Brown, M. Hatfield, and L. Hanson. 2016. Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology. Frontiers in Ecology and the Environment 14:241–251.

Chust, G., I. Galparsoro, Á. Borja, J. Franco, and A. Uriarte. 2008. Coastal and estuarine habitat mapping, using LIDAR height and intensity and multi-spectral imagery. Estuarine, Coastal and Shelf Science 78:633–643.

Colomina, I., and P. Molina. 2014. Remote sensing unmanned aerial systems for photogrammetry and remote sensing: a review. ISPRS (International Society for Photogrammetry and Remote Sensing) Journal of Photogrammetry and Remote Sensing 92:79–97.

Cress, J., M. Hutt, J. Sloan, M. Bauer, M. Feller, and S. Goplen. 2015. U.S. Geological Survey unmanned aircraft systems (UAS) roadmap 2014. U.S. Geological Survey Open-File Report 2015-1032.

Darwin, N., A. Ahmad, and O. Zainon. 2014. The potential of unmanned aerial vehicle for large scale mapping of coastal area. IOP Conference Series: Earth and Environmental Science 18:012031.

Díaz-Delgado, R., C. Cazacu, and M. Adamescu. 2018. Rapid assessment of ecological integrity for LTER wetland sites by using UAV multispectral mapping. Drones [online serial] 3(1):3.

Durban, J. W., H. Fearnbach, L. G. Barrett-Lennard, W. L. Perryman, and D. J. Leroi. 2015. Photogrammetry of killer whales using a small hexacopter launched at sea. Journal of Unmanned Vehicle Systems 3:131–135.

FAA (Federal Aviation Administration). 2016. FAA news: summary of small unmanned aircraft rule (part 107). FAA, Washington, D.C.

FAA (Federal Aviation Administration). 2018. FAA hits 100K remote pilot certificates issued. FAA, Washington, D.C. Available: https://www.faa.gov/news/updates/?newsId=91086&omniRss=news_updates Aoc&cid=101_N_U. (May 2019).

Gonçalves, J. A., and R. Henriques. 2015. UAV photogrammetry for topographic monitoring of coastal areas. ISPRS (International Society for Photogrammetry and Remote Sensing) Journal of Photogrammetry and Remote Sensing 104:101–111.

González-Jorge, H., J. Martínez-Sánchez, M. Bueno, and P. Arias. 2017. Unmanned aerial systems for civil applications: a review. Drones [online serial] 1(1):2.

Groves, P. A., B. Alcorn, M. M. Wiest, J. M. Maselko, and W. P. Connor. 2016. Testing unmanned aircraft systems for salmon spawning surveys. Facets 1:187–204.

Hardin, P. J., V. Lulla, R. R. Jensen, and J. R. Jensen. 2019. Small unmanned aerial systems (sUAS) for environmental remote sensing: challenges and opportunities revisited. GIScience and Remote Sensing 56:309–322.

Hardy, T. B., K. Kollaus, K. Tolman, T. Heard, and J. Tennant. 2012. Aerial assessment of aquatic and riparian habitat in the Brazos River and Blanco River. River Systems Institute, Texas State University, San Marcos, Texas.

Hentz, Â. M. K., P. J. Kinder, J. A. Hubbart, and E. Kellner. 2018. Accuracy and optimal altitude for physical habitat assessment (PHA) of stream environments using unmanned aerial vehicles (UAV). Drones [online serial] 2(2):20.

Hodgson, J. C., S. M. Baylis, R. Mott, A. Herrod, and R. H. Clarke. 2016. Precision wildlife monitoring using unmanned aerial vehicles. Scientific Reports 6:22574.

Hodgson, J. C., and L. P. Koh. 2016. Best practice for minimising unmanned aerial vehicle disturbance to wildlife in biological field research. Current Biology 26:R404–R405.

Howard, B. C. 2017. Watch how drones fight pirate fishing from the sky. National Geographic (January 24). Available https://www.nationalgeographic.com.au/people/watch-how-drones-fight-pirate-fishing-from-the-sky.aspx. (May 2019).

Jensen, J. R. 2017. Drone aerial photography and videography: data collection and image interpretation. J. R. Jensen (self-published e-book), Columbia, South Carolina.

Joyce, K. E. A., S. A. Duce, S. M. A. Leahy, J. B. Leon, and S. W. C. Maier. In press. Principles and practice of acquiring drone-based image data in marine environments. Marine and Freshwater Research. DOI: 10.1071/MF17380.

Kalacska, M., G. L. Chmura, O. Lucanus, D. Bérubé, and J. P. Arroyo-Mora. 2017. Structure from motion will revolutionize analyses of tidal wetland landscapes. Remote Sensing of Environment 199: 14–24.

Kalacska, M., O. Lucanus, L. Sousa, and T. Vieira. 2018. Freshwater fish habitat complexity mapping using above and underwater structure-from-motion photogrammetry. Remote Sensing [online serial] 10(12):1912.

Kislik, C., I. Dronova, and M. Kelly. 2018. UAVs in support of algal bloom research: a review of current applications and future opportunities. Drones [online serial] 2(4):35.

Kiszka, J. J., J. Mourier, K. Gastrich, and M. R. Heithaus. 2016. Using unmanned aerial vehicles (UAVs) to investigate shark and ray densities in a shallow coral lagoon. Marine Ecology Progress Series 560:237–242.

Klemas, V. V. 2015. Coastal and environmental remote sensing from unmanned aerial vehicles: an overview. Journal of Coastal Research 31:1260–1267.

Kopaska, J. 2014. Drones—a fisheries assessment tool? Fisheries 39:319–319.

Krause, D. J., J. T. Hinke, W. L. Perryman, M. E. Goebel, and D. J. Leroi. 2017. An accurate and adaptable photogrammetric approach for estimating the mass and body condition of pinnipeds using an unmanned aerial system. PLoS ONE [online serial] 12(11):e0187465.

Kudo, H., Y. Koshino, A. Eto, M. Ichimura, and M. Kaeriyama. 2012. Cost-effective accurate estimates of adult Chum Salmon, *Oncorhynchus keta*, abundance in a Japanese river using a radio-controlled helicopter. Fisheries Research 119–120:94–98.

Long, N., B. Millescamps, B. Guillot, F. Pouget, and X. Bertin. 2016. Monitoring the topography of a dynamic tidal inlet using UAV imagery. Remote Sensing [online serial] 8(5):387.

López, J. J., and M. Mulero-Pázmány. 2019. Drones for conservation in protected areas: present and future. Drones [online serial] 3(1):10.

Mancini, F., M. Dubbini, M. Gattelli, F. Stecchi, S. Fabbri, and G. Gabbianelli. 2013. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments. Remote Sensing [online serial] 5:6880–6898.

Mulero-Pázmány, M., S. Jenni-Eiermann, N. Strebel, T. Sattler, J. J. Negro, and Z. Tablado. 2017. Unmanned aircraft systems as a new source of disturbance for wildlife: a systematic review. PLoS ONE [online serial] 12(6):e0178448.

Padua, L., J. Vanko, J. Hruška, T. Adão, J. J. Sousa, E. Peres, and R. Morais. 2017. UAS, sensors, and data processing in agroforestry: a review towards practical applications. International Journal of Remote Sensing 38:2349–2391.

Pajares, G. 2015. Overview and current status of remote sensing applications based on unmanned aerial vehicles (UAVs). Photogrammetric Engineering and Remote Sensing 81:281–329.

Ramos, E. A., B. Maloney, M. O. Magnasco, and D. Reiss. 2018. Bottlenose dolphins and Antillean manatees respond to small multi-rotor unmanned aerial systems. Frontiers in Marine Science 5:316.

Raoult, V., L. Tosetto, and J. Williamson. 2018. Drone-based high-resolution tracking of aquatic vertebrates. Drones [online serial] 2(4):37.

Rieucau, G., L. Doksæter Sivle, and N. O. Handegard. 2016a. Schooling herring perform stronger collective anti-predator reactions when previously exposed to killer whales calls. Behavioral Ecology 27:538–544.

Rieucau, G., A. J. Holman, J. C. Castillo, I. D. Couzin, and N. O. Handegard. 2016b. School level structural and dynamic adjustments to risk promote information transfer and collective evasion in herring. Animal Behaviour 117:69–78.

Rieucau, G., J. J. Kiszka, J. C. Castillo, J. Mourier, K. M. Boswell, and M. R. Heithaus. 2018. Using unmanned aerial vehicle (UAV) surveys and image analysis in the study of large surface-associated marine species: a case study on reef sharks *Carcharhinus melanopterus* shoaling behaviour. Journal of Fish Biology 93:119–127.

Sandbrook, C. 2015. The social implications of using drones for biodiversity conservation. Ambio 44(S4):S636–S647.

Smith, C. E., S. T. Sykora-Bodie, B. Bloodworth, S. M. Pack, T. R. Spradlin, and N. R. LeBoeuf. 2016. Assessment of known impacts of unmanned aerial systems (UAS) on marine mammals: data gaps and recommendations for researchers in the United States. Journal of Unmanned Vehicle Systems 4:31–44.

Tamminga, A., C. Hugenholtz, B. Eaton, and M. Lapointe. 2015. Hyperspatial remote sensing of channel reach morphology and hydraulic fish habitat using an unmanned aerial vehicle (UAV): a first assessment in the context of river research and management. River Research and Applications 31:379–391.

Toonen, H. M., and S. R. Bush. In press. The digital frontiers of fisheries governance: fish attraction devices, drones and satellites. Journal of Environmental Policy and Planning. DOI: 10.1080/1523908x.2018.1461084.

Turner, I. L., M. D. Harley, and C. D. Drummond. 2016. UAVs for coastal surveying. Coastal Engineering 114:19–24.

Tyler, S., O. P. Jensen, Z. Hogan, S. Chandra, L. M. Galland, and J. Simmons. 2018. Perspectives on the application of unmanned aircraft for freshwater fisheries census. Fisheries 43:510–516.

Vanderlaan, A. S. M., M. J. Jech, T. C. Weber, Y. Rzhanov, and M. E. Lutcavage. 2014. Direct assessment of juvenile Atlantic Bluefin Tuna: integrating sonar and aerial results in support of fishery-independent surveys. Collective Volume of Scientific Papers ICCAT 71:1617–1625.

Ventura, D., A. Bonifazi, M. F. Gravina, A. Belluscio, and G. Ardizzone. 2018. Mapping and classification of ecologically sensitive marine habitats using unmanned aerial vehicle (UAV) imagery and object-based image analysis (OBIA). Remote Sensing [online serial] 10(9):1331.

Ventura, D., M. Bruno, G. Jona Lasinio, A. Belluscio, and G. Ardizzone. 2016. A low-cost drone based application for identifying and mapping of coastal fish nursery grounds. Estuarine, Coastal and Shelf Science 171:85–98.

Vincent, J. B., L. K. Werden, and M. A. Ditmer. 2015. Barriers to adding UAVs to the ecologist's toolbox. Frontiers in Ecology and the Environment 13:74–75.

Watts, A. C., V. G. Ambrosia, and E. A. Hinkley. 2012. Unmanned aircraft systems in remote sensing and scientific research: classification and considerations of use. Remote Sensing [online serial] 4:1671–1692.

Whitehead, K., C. H. Hugenholtz, S. Myshak, O. Brown, A. LeClair, A. Tamminga, T. E. Barchyn, B. Moorman, and B. Eaton. 2014. Remote sensing of the environment with small unmanned aircraft systems (UASs), part 2: scientific and commercial applications. Journal of Unmanned Vehicle Systems 2:86–102.

Willms, T., and G. Whitworth. 2016. Mapping of critical summer thermal refuge habitats for Chinook Salmon, Coho Salmon, steelhead and Bull Trout in the Nicola River watershed–2016. Habitat Stewardship Program for Species at Risk, Kamloops, British Columbia.

Woodget, A., F. Visser, A. Cracknell, S. Phinn, D. Donoghue, A. Lucieer, C. Varotsos, and A. S. Milas. 2017. Unmanned aerial vehicles for environmental applications. International Journal of Remote Sensing 38:2029–2036.

Yahyanejad, S., and B. Rinner. 2015. A fast and mobile system for registration of low-altitude visual and thermal aerial images using multiple small-scale UAVs. ISPRS (International Society for Photogrammetry and Remote Sensing) Journal of Photogrammetry and Remote Sensing 104:189–202.

Yang, J., and F. J. Artigas. 2010. Mapping salt marsh vegetation by integrating hyperspectral and LiDAR remote sensing. Pages 173–190 *in* Y. Wang, editor. Remote sensing of coastal environments. CRC Press, Boca Raton, Florida.

Zinke, P., and C. Flener. 2013. Experiences from the use of unmanned aerial vehicles (UAV) for river bathymetry modelling in Norway. VANN 48:351–360.