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Principles and practice of acquiring drone-based image data in marine environments

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Abstract. With almost limitless applications across marine and freshwater environments, the number of people using, and wanting to use, remotely piloted aircraft systems (or drones) is increasing exponentially. However, successfully using drones for data collection and mapping is often preceded by hours of researching drone capabilities and functionality followed by numerous limited-success flights as users tailor their approach to data collection through trial and error. Working over water can be particularly complex and the published research using drones rarely documents the methodology and practical information in sufficient detail to allow others, with little remote pilot experience, to replicate them or to learn from their mistakes. This can be frustrating and expensive, particularly when working in remote locations where the window of access is small. The aim of this paper is to provide a practical guide to drone-based data acquisition considerations. We hope to minimise the amount of trial and error required to obtain high-quality, map-ready data by outlining the principles and practice of data collection using drones, particularly in marine and freshwater environments. Importantly, our recommendations are grounded in remote sensing and photogrammetry theory so that the data collected are appropriate for making measurements and conducting quantitative data analysis.

Additional keywords: high resolution, thermal, three-dimensional mapping, UAS, UAV, unmanned aerial system, unmanned aerial vehicle.

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Introduction

Improvements in satellite technology over the past 20 years have markedly increased the value of remote sensing imagery to ecologists (Goodman *et al.* 2013). Yet, with a best ground resolution of 31 cm $pixel^{-1}$ for panchromatic and 1.24 m for multispectral data (Worldview-3 satellite), commercial satellite imagery remains best suited to assessing benthic condition and change at the scale of entire reefs or reef systems (Hamylton 2017*a*, 2017*b*; Roelfsema *et al.* 2018); it struggles to provide the level of detail relevant to biologists and reef managers, who are often interested in benthic condition with significantly finer detail, even down to the scale of individual organisms, plants or colonies (e.g. Perry *et al.* 2012; Richardson *et al.* 2017). At the other extreme, in-water visual or photographic surveys by snorkel or SCUBA can provide this extremely detailed data on reef condition and benthic cover, but their coverage is limited to transects of tens to hundreds of metres (e.g. Leon *et al.* 2015; Chennu *et al.* 2017). Furthermore, the data collected during in-water surveys is traditionally not spatially explicit (Murphy and Jenkins 2010). This means that although researchers can provide, for example, average differences in percentage benthic cover through time, it is often not possible to pinpoint exactly where the changes have occurred. Importantly, determining the 'where' is a critical first step in being able to assess the 'why' behind changes occurring in an ecosystem (Hamylton 2017*b*).

Drone technology fits squarely between these two approaches (Fig. 1). Drones (also called remotely piloted aircraft systems, RPASs, or unmanned aerial vehicles, UAVs) provide the same continuous overhead or 'eye in the sky' perspective as satellites. However, because they operate at a much lower altitude, drones can capture considerably more detailed imagery with pixel sizes in the order of centimetres depending on flying height (Berni *et al.* 2009*a*, 2009*b*; Dunford *et al.* 2009; Flynn and Chapra 2014). In addition, drones can collect imagery under conditions where satellites would be of limited use, such as high cloud cover. Drones also offer greater flexibility in the timing and frequency of image capture, allowing users to capture images at a certain tide stage (e.g. low tide; see Casella *et al.* 2017) or before and after events (e.g. storms; see Ierodiaconou *et al.* 2016). Where in-water surveys are limited in their coverage, drones can survey significantly larger areas while still providing high-resolution information, with the

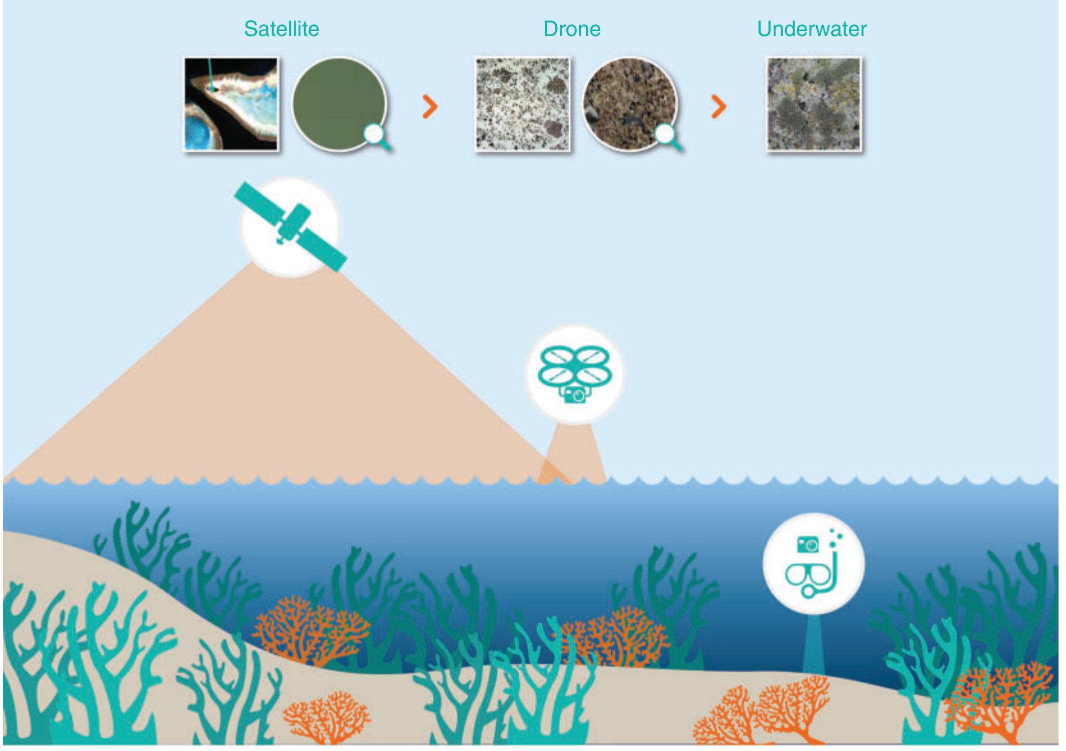

Fig. 1. Varying areas of coverage and scales of observation based on satellite, drone and underwater photography. Image capture altitude is proportional to the area covered and inversely proportional to the level of detail achieved.

added benefit of being spatially explicit and highly replicable (Hamylton 2017*b*). In short, drones are powerful additions to data collection protocols, particularly in marine science.

The advantages of drones have been well documented across a range of disciplines, including agriculture (e.g. Herwitz *et al.* 2004; Berni *et al.* 2009*a*, 2009*b*; Xiang and Tian 2011), emergency management (e.g. Ambrosia *et al.* 2005), terrestrial ecology and wildlife conservation (e.g. Laliberte *et al.* 2011; Wallace *et al.* 2012; Gonzalez *et al.* 2016) and marine science (e.g. Hodgson *et al.* 2013; Casella *et al.* 2017). These advantages include the ability to cheaply and frequently collect high-resolution imagery across reasonably large areas that may be otherwise inaccessible or dangerous. However, in order to collect more than just 'pretty pictures', there are certain principles to follow and the associated challenges are not always well documented in the scientific literature. So, how can researchers incorporate this powerful, and increasingly accessible, new technology into research or monitoring programs? This paper provides practical advice on the principles and practice of using drones for numerous applications in terrestrial and aquatic environments. We describe some valuable marine applications of drone imagery and explain the basics of drone set-up and operation, survey design and safety precautions.

Marine applications

The type of information that can be detected by drones is limited primarily by their payload capacity. Sensor miniaturisation, in combination with increased payload capacity and battery life of small drones (<25 kg), now makes it feasible for researchers to collect data beyond the visible spectrum captured by traditional cameras. Coupled with the high spatial resolution and controlled flight path unique to drone operation, this is a considerable advance in terms of collecting data and ultimately providing information in marine environments (Murfitt *et al.* 2017). Below we highlight just a few of the most common uses.

Two-dimensional habitat mapping

At its most basic, drone imagery can be used to visualise a study site, including benthic composition (Chirayath and Earle 2016) and local fauna, and their use of the space (for a thorough review of this topic, see Colefax *et al.* 2018). These applications are analogous to the site overviews and animal surveys traditionally conducted using low airplane or helicopter flyovers (e.g. Rowat *et al.* 2009; Duke *et al.* 2017; Hughes *et al.* 2017; Sheldon *et al.* 2017). However, for many researchers, hiring manned aircraft is prohibitively expensive. Even with expert staff, manned aircraft flyovers do not necessarily generate the concrete, shareable, quantitative images that are crucial to providing a baseline against which to assess future surveys (Colefax *et al.* 2018).

Downward-facing (nadir) imagery from one or more drone flights can be stitched together to produce image mosaics, or orthomosaics, if the images are geometrically corrected to remove any spatial distortions. With the assistance of an on-board global positioning system (GPS) and supplemented, where possible, with ground control points, the data can also be georeferenced (i.e. located in geographic space with known x and y coordinates). For many marine researchers, a mosaic of visible light imagery alone can provide a helpful context to their

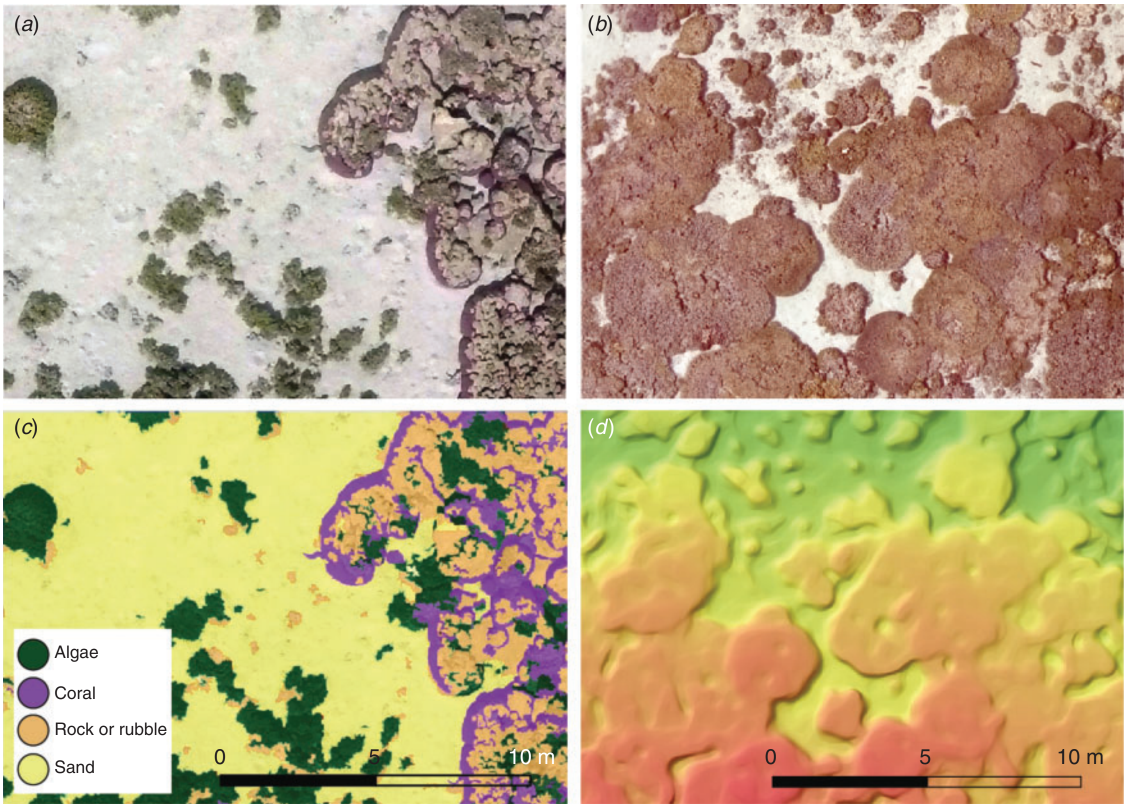

Fig. 2. Using high spatial resolution imagery (*a*, *c*) to derive benthic composition (*b*) surface structure from which to calculate rugosity (*d*). The shading shown in (*d*) is for visual reference only and has not been calibrated to actual depth or structural values.

study sites (Chirayath and Earle 2016). Image data processing using colour information alone, or using colour with shape, size, texture and context information from protocols such as object-based image analysis, can be used to generate habitat maps to better understand the magnitude and location of the changes that are occurring on coral reefs (Leon and Woodroffe 2011; Wahidin *et al.* 2015; Fig. 2). Although both drone and in-water visual surveys can quantify benthic composition, drone imagery is spatially explicit, providing information on the relative location and distribution patterns of benthic components (Chirayath and Earle 2016), as well as serving as a geolocated baseline against which to align and carry out future surveys.

Three-dimensional habitat complexity models

Habitat complexity or rugosity is a crucial aspect for ecology, but can be difficult to assess at appropriate spatial scales (Kovalenko *et al.* 2012). Benthic habitat complexity is traditionally assessed by determining the length of chain required to drape over a horizontal length of 1 m on the reef (Risk 1972; Alvarez-Filip *et al.* 2009). However, chain placement can be subjective, painstaking and damaging to corals. Benthic habitat complexity can be assessed more rapidly using a relative index, but this provides a coarser metric of rugosity and, at times, can be subject to observer bias (McCormick 1994). Regardless of the technique, benthic habitat complexity is a highly heterogeneous characteristic, which means multiple measurements must be taken in order to gain an accurate representation of true rugosity (Storlazzi *et al.* 2016). It is therefore incredibly labour intensive.

Alternatively, considerable research has now been undertaken to assess the benefits of photogrammetry for measuring rugosity (e.g. Friedman *et al.* 2012; Figueira *et al.* 2015; Storlazzi *et al.* 2016). Collecting imagery of a site (whether by drone, autonomous underwater vehicle or using in-water hand-held cameras) with high levels of overlap and sidelap (sometimes called forward and lateral overlap) between images allows every visible part of the benthos to be perceived from a range of angles. This means that high-resolution three-dimensional models of the benthos can then be generated using structure from motion (SfM) algorithms (Leon *et al.* 2015; Casella *et al.* 2017; Fig. 2). These high-resolution benthic complexity maps are permanent records of a site's benthic complexity, and can be revisited in combination with habitat maps of live coral cover, or in time series to identify degradation or improvements in benthic rugosity. They can even be subsampled at a range of resolutions to identify the scale of benthic complexity of functional importance to different taxa (Richardson *et al.* 2017). This method of quantifying benthic complexity can also be compared directly with traditional methods of in-water complexity measures to assess the accuracy of staff undergoing field training, or to calibrate a transitional period from using in-water to imagery-based methods when contributing to long-term datasets. Furthermore, this image-based approach using SfM is entirely non-intrusive and will not damage the benthic habitat (Ferrari *et al.* 2016).

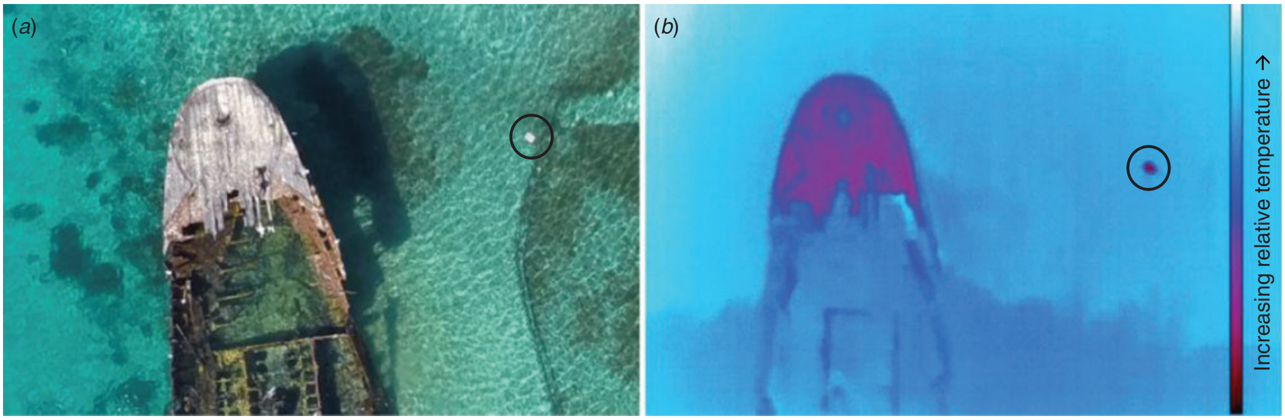

Fig. 3. Comparison of imagery acquired from (*a*) a drone-based day-time visible Sony a7R digital single-lens reflex camera (Sydney, NSW, Australia) and (*b*) a night-time thermal FLIR a65 camera (Wilsonville, OR, USA). Note that the bright feature circled is a calibration thermometer and buoy. Thermal imagery is captured at 0400 hours for optimal results from an altitude of 60 m. A cooler body of water is clearly seen in the bottom portion of the thermal image.

Drone imagery and SfM algorithms have been widely and successfully used to derive XYZ point clouds in terrestrial applications (Smith *et al.* 2016; Kalacska *et al.* 2017; Marteau *et al.* 2017; Mlambo *et al.* 2017). However, underwater applications of photogrammetric measurements need to account for two additional limitations. The first is water clarity, limiting the application of photogrammetry to areas with calm (i.e. no wave turbulence) and very clear waters, such as offshore coral reefs. The second challenge is light refraction as it crosses the air–water interface (Chirayath and Earle 2016; Casella *et al.* 2017). Refraction correction techniques, such as the simplified version of Snell's Law for nadir SfM imagery proposed by Woodget *et al.* (2015) or the multicamera refraction correction proposed by Dietrich (2017), go some way towards overcoming this challenge. Maas (2015) also presented an elegant model to reduce the degradation of geometric accuracy in underwater photogrammetry, but current off-the-shelf photogrammetry software packages do not provide such solutions as yet. Fluid lensing technology, presented by Chirayath and Earle (2016), also potentially offers a novel solution to distortions caused by the water column, but is still limited to use in clear, shallow water (<10 m) and requires extreme computer processing. For the above reasons, realistic use of SfM from drone imagery of submerged environments is limited to exceptionally calm, clear days with minimal water overlaying the features of interest. Alternatively, underwater SfM may be appropriate.

Sea surface temperature and animal monitoring

Currently, remotely sensed thermal data is acquired by satellites such as NASA's Landsat 8, which has a pixel size of 100 m and a revisit frequency of 16 days. Alternatively, the moderate-resolution imaging spectroradiometer (MODIS) sensor on the Terra satellite acquires data daily, but with a 1-km pixel size. These spatial and temporal resolutions are valuable for capturing thermal patterns at global and regional scales, but are not able to elucidate the spatial heterogeneity in the thermal experiences of individual coral colonies. Thermal information at finer scales is required to understand events such as coral bleaching. Although an array of in-water temperature loggers could conceivably collect sea surface temperature (SST) data at the fine scale most relevant to coral bleaching (Gorospe and Karl 2011), such a system is expensive, labour intensive to deploy and unreasonable to move between study sites. Furthermore, such point-based data collection requires predictive modelling to 'fill the gaps' between individual points in the array, whereas remotely sensed imagery provides spatially contiguous data that can be readily collected and compared among several study sites. In our experience, drone-mounted thermal sensors can collect contiguous relative SST imagery with a ground sample distance of 6–12 cm (Fig. 3), depending on flight altitude and the resolution of the camera itself. Similar work has also been conducted by Lee *et al.* (2016), who demonstrated the benefit of using drone-based SST imagery for mapping groundwater discharge. Repeated imaging through time may elucidate fine-scale water circulation patterns, particularly when used in conjunction with the three-dimensional benthic rugosity models described above. However, calibration and validation of thermal sensors for absolute temperatures is challenging, and this work is the subject of a follow-up publication (S. W. Maier and K. E. Joyce, in prep.).

An important limitation of remotely sensed SST data, be it from satellites or drones, is the depth to which temperature can actually be detected. Observations by infrared sensors are essentially limited to the top 10 μm of a waterbody, often referred to as water 'skin' temperature (Kunzer and Dech 2013). In well-mixed systems, skin temperature is closely related to temperature at greater depths (e.g. 1 cm, 50 cm, 1 m, 5 m). Temperature as a function of depth must then be modelled, using *in situ* measurements, to convert remotely sensed skin temperature to SSTs at depths that are meaningful for corals and other undersea organisms.

In addition, remotely sensed thermal data are highly dependent on the thermal emissivity properties of the material being imaged (i.e. how effective it is at emitting energy as thermal radiation). For example, water, with its high emissivity coefficient (~0.95, depending on its composition), will always appear warmer in thermal images than steel (emissivity 0.23–0.83, depending on age and surface tarnish), even if the two materials are at the same true temperature. As such, quantitative thermal

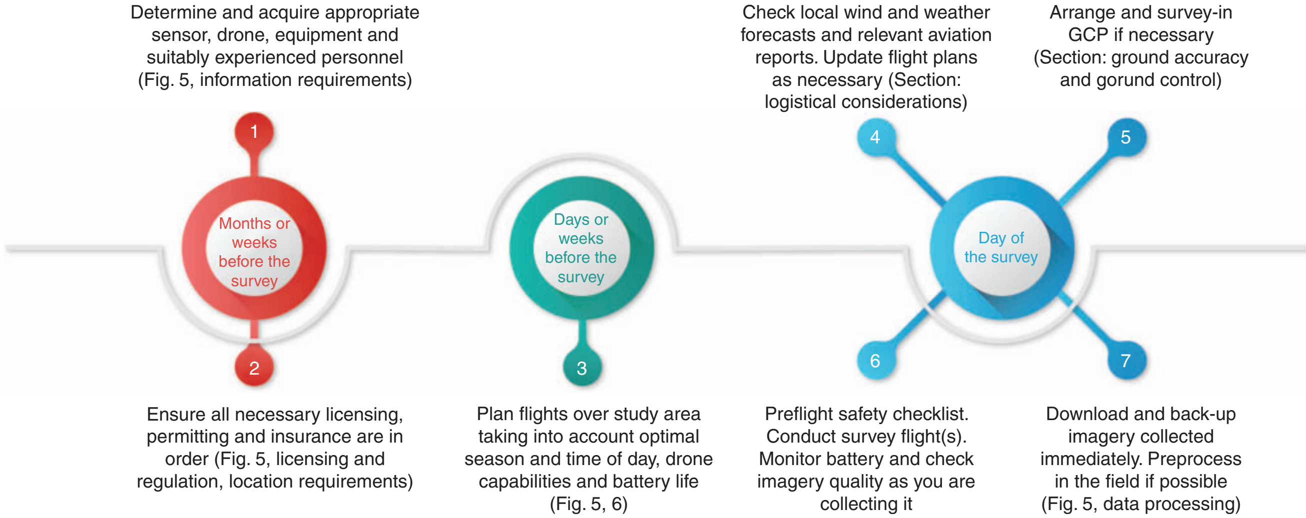

Fig. 4. Drone data collection workflow showing Steps 1–7 and the estimated time frame for each step. GCP, ground control point.

imaging is best applied to homogeneous landscapes (e.g. water), unless users are prepared to carry out material-specific emissivity corrections on the dataset (Kunzer and Dech 2013).

Drone-mounted thermal cameras can also be used for spatially extensive and non-invasive animal observations, such as identifying and counting seals (Seymour *et al.* 2017), as long as safe and legal minimum distances from these animals are respected (Junda *et al.* 2015). Owing to the low energy levels of electromagnetic radiation in the thermal infrared range, users should expect the ground sample distance of thermal cameras to be coarser than visible light cameras flown at the same altitude. The size of the animal or feature of interest must be taken into account when identifying the required image pixel size, and therefore drone flight height. As a whole, thermal imaging offers great potential to enrich faunal surveys, and is particularly suited to areas where human access is limited, either logistically or for safety reasons (McCafferty 2007; Gonzalez *et al.* 2016).

Thermal cameras are often best operated at night to avoid sunlight contamination and to more clearly identify nested or nocturnal animals. However, be aware that night-time flight may also require additional certification from airspace governing authorities.

Building drone capability

Building an organisation's, or an individual's, drone capability (i.e. the ability to successfully collect data using drones) takes planning, time and money. Fig. 4 shows a typical workflow for drone-based data collection from preparation through to surveying. Estimated time frames are provided, as well as references to the location in this paper of further information on each of the steps.

Application requirements

In some cases, drones are seen to be a solution looking for a problem. It is therefore important to understand the conditions under which they are best used and the type of information that they are suitable for providing. Before determining whether drones are appropriate for any particular application, the user should return to some remote sensing fundamentals that drive the selection of optimal image datasets. This will determine the sensor and drone infrastructure that is required to achieve the end goal (Fig. 5, information requirements).

Logistical considerations

Several logistical and administrative protocols are inherent to the use of drones, including staff training and licensing, liability insurance and guidelines or permits for operating in areas such as the Great Barrier Reef Marine Park. Jurisdiction-specific regulations restrict drone-based activities in national parks, around marine mammals and other areas of wildlife activity, such as seabird nesting and foraging. Care should also be taken to minimise the chance of drone–wildlife interactions in general through the selection of suitable take-off and landing zones, altering flight timing or adopting specific flight techniques, such as those documented by Junda *et al.* (2015). The comprehensive review by Mulero-Pázmány *et al.* (2017) on the effect of drones on wildlife clearly demonstrates the need for a sit- specific plan that takes into account the time of day, type of wildlife in the area and size of drone to be flown.

When considering whether to incorporate drone-collected imagery into your work, it is important to identify trade-offs and where you may be willing to compromise. For example, as drones increase in size and expense, generally they will be able to provide higher-quality data (spatially, spectrally or both) over larger areas. However, an increase in size also introduces challenges with battery transportation and may require special protocols for transporting 'dangerous goods'. Larger drones may require an additional licence for remote pilots and can be cumbersome to operate, particularly if considering boat-based launch and retrieval.

As a general rule, fixed-wing aircraft are more efficient than rotary and are able to survey larger areas (Floreano and Wood 2015). However, they require large areas for take-off and landing that may not suit many marine operations. As a compromise between fixed-wing and rotary drones, recent progression in vertical take-off and land (VTOL) drone technology (Watts *et al.* 2012) is an exciting step forward for marine applications in the future. All things considered, for ease of operation, safety and budget, users should consider the smallest and cheapest drone that will satisfy their mission requirements.

Finally, it is important for all staff to have appropriate equipment and training to monitor radio channels and airspace for other users, particularly manned aircraft such as seaplanes and helicopters.

Information requirements

What is your feature of interest?	The level detail required to identify and quantify targets of interest will affect the sensor chosen for the job. For example, measuring a biophysical variable such as chlorophyll content is likely to require a more sophisticated sensor than one used for mapping the difference between corals and sediment.
How big is your feature of interest?	Small features require low-altitude flight: aim for a pixel size one-tenth the size of the feature of interest (also see Fig. 2).
Over what size area does your feature of interest occur?	Large areas (>200 ha) may be more suited to satellite data, or fixed-wing instead of multirotor systems (see also Fig. 1). Battery life (normally 10–30 min for small drones) and line of sight restrictions limit the area that can be covered in any one flight.
Is it easy to identify using human eyesight or does it blend with its surrounds?	May need to consider multispectral or even thermal imaging. Different drones have different recommended payloads. Some drones may be flexible with payload offerings, others not. Payload type and weight will also affect licensing requirements and insurance costs.
Does it look differentat different times of the year, season or day (e.g. flowering, leaf colour)?	May affect on timing of surveys. Consider also the necessary additional licence exemptions to fly at night.

Licensing and regulations

Do any of your employees have their remote pilot's license?	Licences are no longer necessary in Australia for flying craft weighing <2 kg, but insurance may be challenging without a licence.
Have you considered a remote Aircraft operator's certificate (ReOC - if in Australia)?	Once an expensive venture, this is now relatively easy to obtain and will allow you to apply for exemptions to some of the regulations, as well as access public liability insurance.
Do you have public liability insurance?	Many insurance companies will insure the drone itself, but consider your requirement to insure for damages in the event of an accident.

Location requirements

Are there any aviation restrictions in the area in which you hope to fly (e.g. close to airports, approach paths, military zones, populous areas)?	May need to lodge exemption applications (only possible if your oganisation holds a ReOC)
Will you be working in a national park, marine park or local council area?	May need a permit.
Will you be able to launch and recover close to the survey area?	Line of sight regulations restrict the distance that drones can be flown. A long flight distance to the starting point of the survey will limit the size of the survey area itself. Visual obstructions such as hills and trees will also affect drone visibility.
Is the size of the launch and recovery area sufficient for your craft type?	Fixed wings require large areas; consider rotary or vertical take-off and land options.

Data processing

Hardware	Access to computing power and data storage for data processing.
Do you have access to remote Sensing and gis software?	Consider cost of licensing to process and analyse the data, or possibility of open source or for service cloud-band options.
Do your staff have an appropriate level of training to plan and execute a mission, as well as to conduct the analysis?	Consider investing in staff professional development or outsourcing.

Other administrative and logistical considerations

What is your timeline for trialling and implementing a solution?	Purchasing equipment can be done relatively rapidly. Setting up staff training and workflows will take considerably longer.
What is your budget?	Consider redundancies; spare batteries and chargers; additional accessories, such as landing pads, tablets, personal protective equipment; training, insurance, licensing.

Fig. 5. Defining your drone capability requirements. Note that the regulations listed here are current at the date of submission, although readers should always confirm with the local aviation safety body in their country of operation. In Australia, this is the Civil Aviation Safety Authority.

Flight planning

To achieve the best orthomosaics, users should aim to keep the survey area to a square or rectangle shape. Because mosaic products tend to decrease in accuracy towards the edges where overlap and sidelap between images decreases, the rectangular shape maximises the area of high-quality processed data. The survey area should be larger than the actual region of interest to ensure all of it is captured near nadir (i.e. where there is minimal distortion at the centre of each contributing photographic frame) with the required level of overlap and sidelap. To create three-dimensional surface models, it is important to capture an area even larger still, to capture off-nadir views from all directions. As much as 90% overlap and 85% sidelap can be required for these applications to ensure that the appropriate number of tie points between images can be found. We have found this high overlap to be particularly important when mapping submerged features and contending with sun glint and partially obscured features (see below). Recommended overlap and sidelap are target and software dependent, so we refer the reader to user manuals of software, such as Pix4D (www.support.pix4d.com, accessed 21 May 2017) or Agisoft Photoscan (www.agisoft.com, accessed 21 May 2017). To assist in planning, Fig. 6 shows how the ground sampling distance (i.e. the area of the ground covered by each pixel) is influenced by flight altitude. Flight planning software automatically calculates fight paths over the defined study area based on user-specified inputs of flying altitude, desired overlap and sidelap and sensor characteristics. The software will predict the flying time required to complete the mission. Based on this time and your knowledge of your drone's battery capabilities, you can determine how many flights will be necessary to cover the study area. Remember that operational battery life is lower than the maximum flight time specified in the manual, which is measured under 'ideal' conditions with no reserve. In addition, batteries do not discharge at an even rate, with the discharge rate increasing markedly below a certain level (Traub 2016). It is important to allow yourself a safety buffer to return and land safely even if unforeseen circumstances arise. Wind and payload will also affect how long the drone's battery lasts. Always aim to land with a minimum of 25% battery life and closely monitor the battery level using your ground control system (remote control, tablet or laptop) as you fly.

Considerations specific to working over water

As outlined above, working with drones over water can yield extremely valuable data about a range of variables, sometimes unobtainable by any other means. However, working over water requires some additional considerations and planning to ensure the success of the mission. Two major factors affect the quality of images acquired during a survey of submerged features: sun glint and subsurface illumination (Mount 2005). Sun glint (or sun glitter) occurs when light is reflected back to the sensor by the surface of the water, obscuring what is beneath it (e.g. Fig. 7). It presents a significant challenge when capturing drone

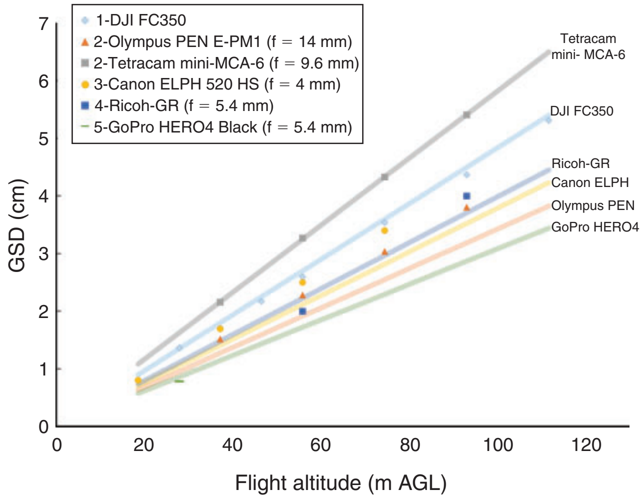

Fig. 6. The ground sampling distance (GSD) achieved with a given sensor at different flight altitudes as reported in the literature. Lines show the theoretical GSD calculated based on the focal length (f) of the sensor. Data are from: 1, Perroy *et al.* (2017) (DJI, Shenzhen, P.R. China); 2, Peña *et al.* (2015) (Olympus, Tokyo, Japan; Tetracam, Chatsworth, CA, USA); 3, Dandois *et al.* (2015) (Canon, Tokyo, Japan); 4, Chiabrando *et al.* (2011) (Ricoh, Tokyo, Japan); 5, Casella *et al.* (2017) (GoPro, San Mateo, CA, USA). AGL, above ground level.

imagery of aquatic environments (Flynn and Chapra 2014). However, the extent to which sun glint affects the resultant mosaic can be managed and overcome with careful flight planning (Mount 2005). We believe that it is best to avoid glint contamination in the first place, rather than have to correct the imagery during postprocessing. To do this, the main considerations are time of image capture (and corresponding solar position), flight direction and camera angle.

Solar position during image capture is important. The solar azimuth is a measure of where in the sky the sun is or will be located. It is measured in degrees clockwise from north for a given observer point at a given time (Fig. 8). The elevation angle (also called the altitude angle or sun angle) refers to the position of the sun in the sky as an angle from the horizon (i.e. at sunrise, the sun elevation angle will be 0°). As a general rule, sun glint will be minimal when imagery is captured when sun elevation is less than 35° (Mount 2005; i.e. early in the morning). Avoiding mapping missions over water around midday will ensure the glint of reflected sunlight is on the edge of imagery rather than the centre, and therefore can be more easily removed during imagery processing. However, this limits the amount of light available and reduces the depth to which imagery is effective, and can result in strong shadowing in images of three-dimensional surfaces. It also restricts the time available to capture imagery and may not fit with tide and other logistical considerations.

To capture good-quality imagery when the sun is higher in the sky, the flight path should be planned such that the drone is flying either directly towards or away from the sun azimuth (i.e. the azimuth ±180°). Fig. 8 shows how to calculate the optimal flight direction based on solar position. Either direction is fine if the

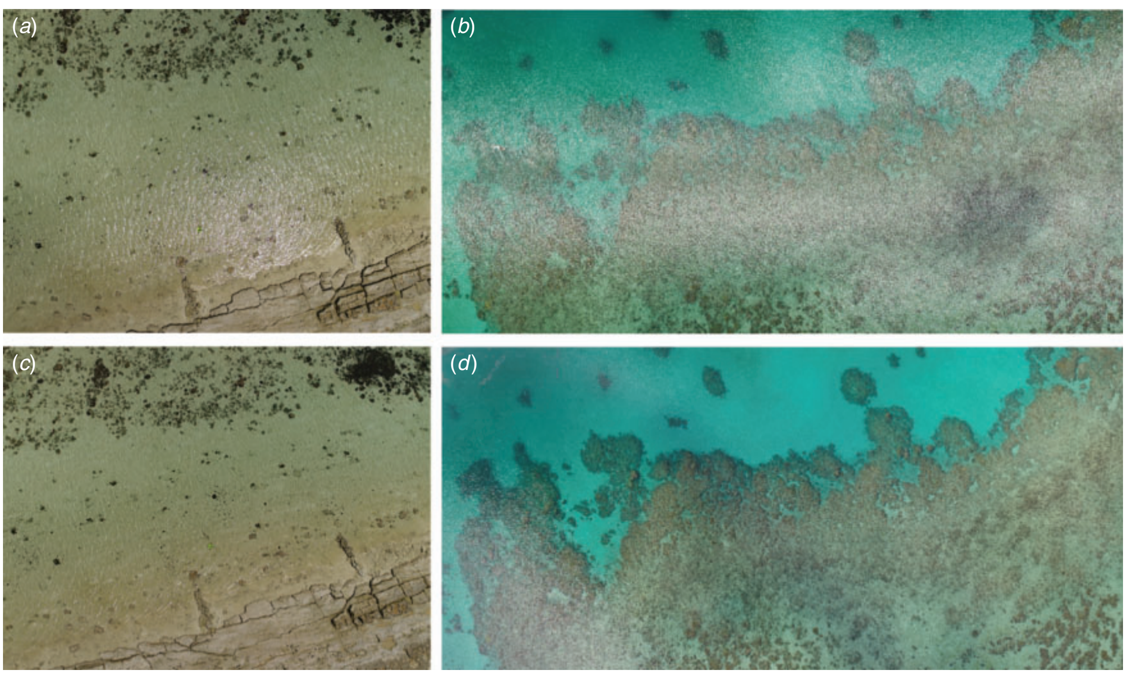

Fig. 7. (*a*, *c*) Images taken at the same location at 40 m altitude at mid-day at Heron Reef. The image in (*a*), which is affected by sun glint, was taken with the camera at nadir, whereas the image in (*c*) was taken with the camera angled slightly off nadir, and the sun glint is minimised. (*b*, *d*) A mosaic of the same area of Ellison Reef. In (*c*), the area was surveyed between 1320 and 1330 hours with the camera at nadir, whereas in (*d*) the image was surveyed between 1420 and 1430 hours with the camera slightly off nadir.

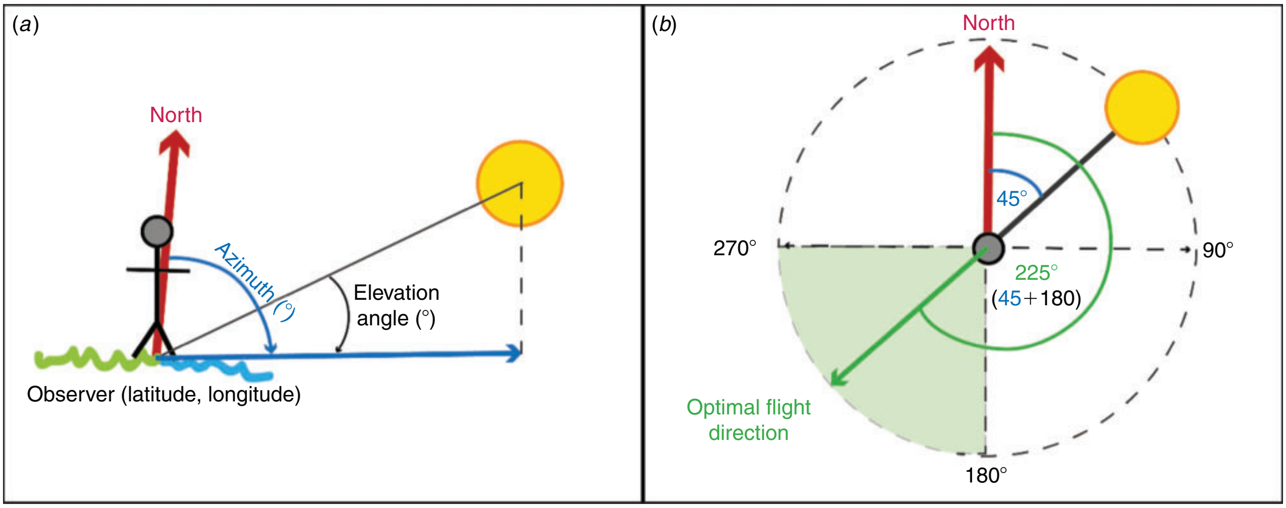

Fig. 8. (*a*) Solar azimuth and elevation angle at an observer's location are defined with respect to north. (*b*) How to plan the optimal flight direction to minimise sun glint in imagery captured over water based on the sun azimuth at your location and time.

sensor is at nadir (pointing vertically straight down), but the drone orientation in flight should be kept constant across the flight in order to more easily crop sun glint effects across all the photographs taken during the flight. This is simple when using a multirotor drone, although it is not possible to fly backwards with a fixed wing. If using the latter, it may be necessary to only obtain imagery every second flight line, or to apply alternating cropping algorithms to alternating flight lines. Alternatively, tilting the camera angle slightly off nadir will reduce and move glint to the edges of the imagery so that it has less effect on the mosaicked product (Fig. 7). We have found an off-nadir angle of 15° to be an acceptable compromise between reducing glint and introducing oblique distortions to imagery. Geometric error will be introduced because of the off-nadir imagery, but high degrees of overlap (oversampling) will help mitigate this (Flynn and Chapra 2014). Georeferencing after mosaicking will most likely also be necessary. Further, if a camera is angled slightly off nadir, then drone orientation in flight should always be directly away from the sun (i.e. in the direction of sun azimuth ±180°). This means that the drone will be flying backwards for half the survey. Several online services are available to calculate the sun azimuth and elevation angle for a given location at a given time, such as Geoscience Australia's sun and moon position calculator (http://www.ga.gov.au/geodesy/astro/smpos.jsp, accessed 21 May 2018).

It is possible to check the imagery on your ground station (i.e. tablet or smartphone) as you are capturing it to find the balance between oblique (off-nadir) capture and minimal glint. Collecting oblique imagery has implications on the ground sampling distance (GSD) with pixels covering a smaller area in the foreground than the background of an image (Hohle 2008; Pepe and Preszioso 2016) and can make processing more difficult (Grenzdörffer *et al.* 2008). Indeed, Casella *et al.* (2017) note that bathymetric reconstruction works better on images taken at nadir because peripheral areas of a scene are more strongly affected by water refraction.

Even with a slight camera tilt and optimal flight direction, sun glint may still appear in individual images. However, if the glint is towards the edge of an image, a high-quality orthomosaic can be created if high levels of overlap and sidelap are achieved (Fig. 7). If the drone is continually capturing imagery while it is flying (as opposed to hovering for capture), increasing the frontlap will not affect the area of coverage or the time taken to complete the flight. This holds true until such a frequency where the camera focus, capture and save process are no longer able to keep up with the speed of the drone in flight. However, increasing the sidelap will certainly reduce areal coverage. Regardless of glint, increasing frontlap and sidelap will lead to a higher-quality mosaic and digital surface model. If glint is unavoidable at the time of image capture and persists through the mosaicking process, a simple post-processing routine may be an option if a camera with a near-infrared sensor has been used (Hochberg *et al.* 2003).

Using polarising filters or working on a cloudy day with diffuse light are alternatives that reduce sun glint at the time of image capture. However, working on a cloudy day means the amount of light reaching the subsurface will be reduced. The level to which this affects available light will, of course, depend on the cloud thickness and time of day. On cloudy days, capturing data closer to midday when the sun is at full strength can be a viable compromise (Kay *et al.* 2009).

It is important to also consider water quality, wind and sea state when planning image collection flights. Certain aquatic environments lend themselves better to aerial mapping than others. Low-turbidity conditions and shallow regions are best, even better if they are tidally exposed. The presence of waves or surface ripples can hinder subsurface visibility in imagery (Mount 2005). Although most commercially available drones are able to fly in winds up to 20 knots (~10.3 m s^{-1}), wind speeds greater than ~5–10 knots (2.5–5 m s^{-1}) can create ripples and waves on the water surface that limit image quality (Mount 2005).

When launching a drone from a boat, remember that the boat may move on its anchor during your survey. If the boat moves during your flight, the 'home' location stored by your drone before it takes off may be over the water. It is possible to create a dynamic home, whereby the drone continually updates the home location based on that of the controller. However, in case of lost connectivity between drone and controller, this can be erroneous and manual landing is preferable.

Accuracy and ground control

As with all remotely sensed data and mapping products, appropriate geometric processing and georeferencing are required to position the image, derive accurate measurements, such as distance, perimeter, area and elevation, and to perform precise change detection analyses. Although drones do have on-board GPS units that can be used to tag images with coordinates at the time of image capture, their accuracy is typically approximately ±5 m, depending on the specific unit itself as well as the satellite configuration and atmospheric conditions at the time of acquisition. Further errors can be introduced if the camera is pointed off nadir so that the area it images does not necessarily correspond to the GPS location of the drone. This means that without additional ground control, it is not possible to derive highly accurate absolute measurements of location, area, height, volume or changes in any of these parameters.

If accurate and absolute XYZ measurements are mission critical, ground control points (GCPs) must be deployed and their location recorded within the survey area. The number and spatial distribution of GCPs and the capability of the GPS unit used have important effects on the accuracy of results (James *et al.* 2017). Many studies suggest using between 10 and 20 GCPs (Clapuyt *et al.* 2016; Tonkin and Midgley 2016). However, there will be a trade-off between what is desirable and what is realistically achievable.

To achieve accurate absolute measures of vertical elevation a survey-grade total station or real-time kinematic differential GPS (1-cm horizontal and 2-cm vertical accuracy) is required to position the GCPs (Harwin and Lucieer 2012). This equipment is expensive and can only be used in intertidal or shallow areas (e.g. Bryson *et al.* 2016) because receivers do not work underwater. Indeed, laying out and accurately surveying GCPs is challenging, particularly underwater, and in many cases is not feasible. Where survey-grade positioning equipment is not available, GCPs can be configured in a triangle with each side of a known length (e.g. Bryson *et al.* 2013). This allows for absolute scaling corrections within the image (i.e. distances, areas and volumes can be accurately and precisely calculated; Bryson *et al.* 2013). Where drones are used to survey an inaccessible area, collecting GCPs may not be possible at all. In these cases, the accuracy limitations of the on-board GPS must be taken into account when presenting and interpreting the results, but will not preclude data collection or analysis.

Calibrating and validating

In some cases it may be appropriate to use drone imagery as a source of *in situ* data for ground truthing (calibration, validation or both) of coarser-scale products such as satellite data. However, in other instances the drone data itself should be ground truthed. We suggest that calibration and validation of drone imagery based on field measurements may be required in the following circumstances:

- when the features of interest in a submerged environment may be partially obscured by the intervening water column so there is uncertainty in identification due to light refraction or water quality despite an otherwise high spatial resolution
- when undertaking quantitative mapping of variables where the absolute value of the variable of interest needs to be measured and extrapolated (e.g. bathymetry, elevation, temperature, biophysical variables)
- when the size of the feature of interest is smaller than or approaching the size of the ground sampling distance (i.e. the pixel).

Summary

Using drones for a variety of research applications offers the opportunity to change our perspective on the environment. In marine research, the advances offered by drones is arguably on par with the extent to which SCUBA diving revolutionised underwater research 70 years ago. Incorporating drones as legitimate research tools will empower scientists around the world to collect relevant, quantitative, spatially explicit, extensive and replicable data for a range of terrestrial, marine and freshwater habitats. However, we also caution that careful consideration of data acquisition and processing, outlined herein, needs to be undertaken if drones are to move beyond the realm of providing ‘pretty pictures’ and into delivering robust scientific and management information.

Conflicts of interest

The authors declare that they have no conflicts of interest

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