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INTERDISCIPLINARY PERSPECTIVES

Location, location, location: considerations when using lightweight drones in challenging environments

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Abstract

Lightweight drones have emerged recently as a remote sensing survey tool of choice for ecologists, conservation practitioners and environmental scientists. In published work, there are plentiful details on the parameters and settings used for successful data capture, but in contrast there is a dearth of information describing the operational complexity of drone deployment. Information about the practices of flying in the field, whilst currently lacking, would be useful for others embarking on new drone-based investigations. As a group of drone-piloting scientists, we have operated lightweight drones for research in over 25 projects, in over 10 countries, and in polar, desert, coastal and tropical ecosystems, with many hundreds of hours of flying experience between us. The purpose of this paper was to document the lesser-reported methodological pitfalls of drone deployments so that other scientists can understand the spectrum of considerations that need to be accounted for prior to, and during drone survey flights. Herein, we describe the most common challenges encountered, alongside mitigation and remediation actions that increase the chances of safe and successful data capture. Challenges are grouped into the following categories: (i) pre-flight planning, (ii) flight operations, (iii) weather, (iv) redundancy, (v) data quality, (vi) batteries. We also discuss the importance of scientists undertaking ethical assessment of their drone practices, to identify and mitigate potential conflicts associated with drone use in particular areas. By sharing our experience, our intention is that the paper will assist those embarking on new drone deployments, increasing the efficacy of acquiring high-quality data from this new proximal aerial viewpoint.

Introduction

Lightweight drones are now firmly established as part of a remote sensing surveying methodology and the scientific literature is replete with examples of drone technology being used for a multitude of purposes including conservation (Koh and Wich 2012), wildlife monitoring (Christie et al. 2016), plant inventory mapping (Husson et al. 2016), biomass estimation (Cunliffe et al. 2016), coastal morphological mapping (Long et al. 2016), coral reef monitoring (Casella et al. 2016), disaster response (Nedjati et al. 2016) and precision agriculture (Bukart et al. 2017). Many environmental science, ecology and conservation applications of drone technology will inherently encounter and have to overcome common challenges and problems. Despite this, these communities lack a common understanding and shared protocols for addressing these challenges, often making the acquisition of drone data collection more problematic and open to error, particularly for those less familiar with the technology.

The ability to deploy drones in a variety of different environments leads to site-specific and user-specific data collection methods. This in turn creates a plethora of methodological challenges, many of which remain unreported in the scientific literature. This is because the style of scientific papers is such that it is rarely required, or indeed attractive to share the broader considerations of drone deployments with the reader; instead the focus is placed on describing flight parameters or details of image capture and data processing. As a group of scientists who are well practiced in deploying lightweight drones, we can attest that even in low-risk deployment scenarios, methodological issues are experienced regularly, requiring a change in approach or compromise. The frequency and severity of such issues are amplified when deploying drones in challenging environments and in parts of the world where drone operations are not well-understood by local communities and resources are limited. This dearth of detailed, practice-based methodological insight into drone deployment considerations means that scientific drone users are likely to be duplicating efforts and it also presents a barrier to those wishing to begin using drone technology, since many helpful operational details remain buried in user forums of online drone groups (e.g. http://diydrones.com/).

Drawing on our extensive collective experiences using lightweight (sub-7 kg take-off-weight) drones in diverse locations such as deserts in the USA, Arctic tundra in Canada, coral atolls in the Maldives, and tropical rainforests in Indonesia and Brazil (Fig. 1), this paper provides a practice-based overview of the methodological challenges faced by drone operators in field settings. Alongside, we present some of our tested solutions to these methodological issues to aid scientists working in ecological, conservation and environmental research, to support the efficient deployment of drone technology and underpin the collection of high-quality scientific data. Our work has been exclusively with optical sensors, although many of the challenges faced are not sensor specific. We also provide sections on environment specific challenges, however many challenges may be encountered in more than one type of environment (Table 1). We do not cover the specific considerations for drone operations around wildlife as this has already been discussed by others (e.g. Ditmer et al. 2015; Pomeroy et al. 2015; Vas et al. 2015; Hodgson and Koh 2016). In addition, scientists rarely write about the cultural and ethical implications of their practices, and therefore we discuss the importance of considering ethical issues prior to undertaking drone operations and offer some guidance for ethical assessment of drone operations. It is too difficult to cover every type of drone-sensor operation, so this paper is primarily focused on discussing lightweight (<7 kg take-off-weight) fixed wing and multirotor drones equipped with photographic equipment for ortho-mosaic (e.g. Husson et al. 2014) and structure-from-motion (SfM) photogrammetry (e.g. Smith et al. 2015) type applications. We begin this paper by providing several key operational guidelines that will assist scientists working in most field settings.

Considerations for Safe Deployment

Pre-flight planning

Safety of drone operations is paramount to researchers, for the obvious reasons of minimising risks to participants, bystanders and other organisms, but also to ensure delivery of useable scientific data and safe return of equipment. A key stage in safe deployment of drone technology is pre-flight planning, which is a relatively simple procedure but, as we have found, can involve considerations of complex issues in some settings. All drone operations should involve a critical pre-flight site check, usually initiated as a desk-based assessment and supported by a survey of the immediate surroundings once on-site. Pre-flight planning is very easy to achieve using various tools to assist the operator in (i) making optimal decisions about where and when it is safe to fly, (ii) identifying safe locations for take-off and landing and (iii) becoming conversant with the regulations governing drone operations, which can differ between countries and sites.

Making decisions about when and where it is safe to fly

In many developed countries, online databases exist detailing information on airspace restrictions, for example Notices to Airmen (NOTAMs). Increasingly, mobile applications can provide near-real-time information on the location of other airspace users (e.g. http://notaminfo.com, http://dronesafe.uk/drone-assist). During drone operations, we commonly establish contact with regional civilian and military air traffic control (ATC). It can often take time to identify the appropriate contacts for relevant authorities such as ATC, but doing so can help alleviate

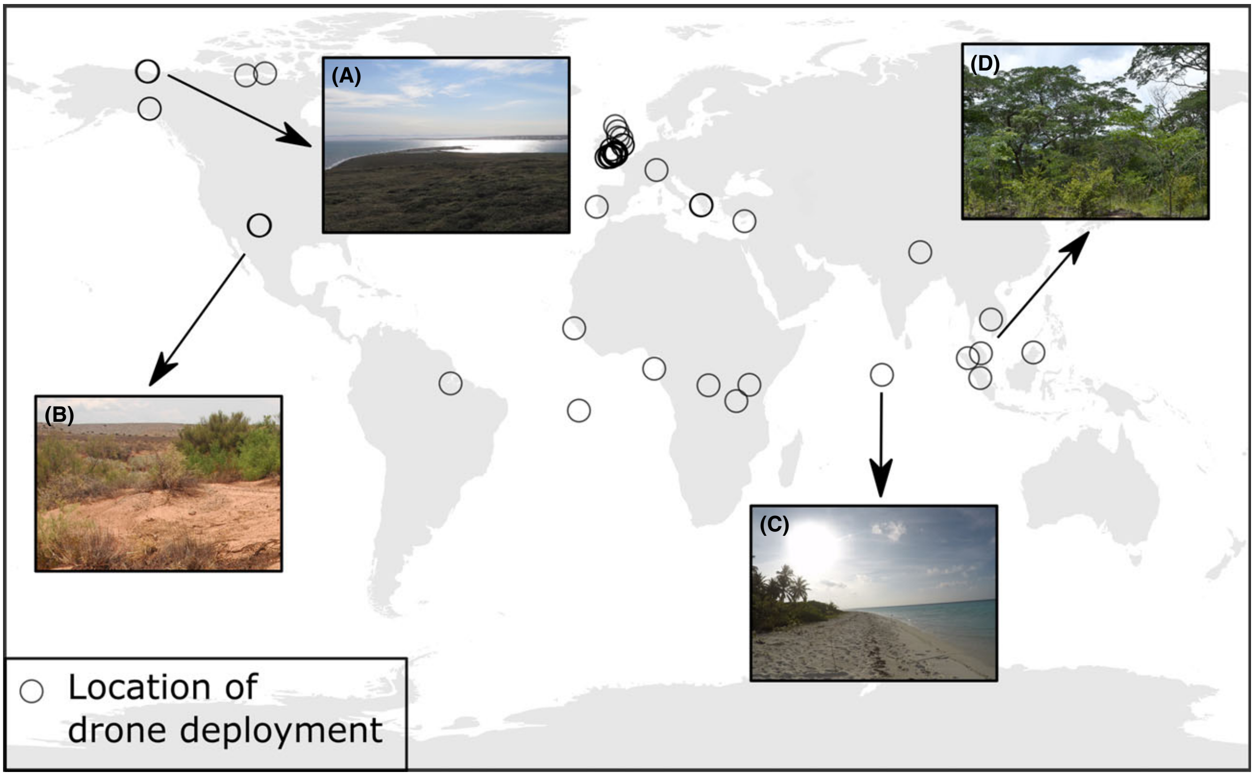

Figure 1. The geographical diversity of locations where we have successfully or unsuccessfully deployed lightweight drones for collection of proximal remote sensing data, including (A) arctic, (B) desert, (C) coastal and (D) tropical forest.

Table 1. Challenges faced during drone operations and the environments in which they can occur.

	Specific challenge							
Operating environment	Safety and regulation	Societal considerations	Wind	Fine particles	Solar effects (glint, shadows, albedo)	Spatial constraint of data products (Difficulties deploying/ locating GCPs)	Telemetry issues	Topography issues
Coastal	✓	✓	✓	✓	✓	✓		✓
Dryland	✓	✓	✓	✓				✓
Polar	✓	✓	✓		✓			✓
Dense forest	✓	✓	✓			✓	✓	✓
High altitude	✓	✓	✓					✓

interruptions in data collection and prevent near misses with aircraft. For example when flying near Land's End Airport in Cornwall, UK (but outside of an official aerodrome traffic zone), we obtained the number of the airport ATC tower from the Internet and liaised with them. This allowed them to create a temporary restricted zone around our operations and to notify any incoming aircraft. On completion of flight operations, we again informed the ATC and the restriction was removed. In summary, a key to safe flying anywhere in the world is to keep other air users informed; in our experience, local ATC managers would rather know of drone operations so that appropriate measures can be enacted (e.g. NOTAMs). Even if official channels are difficult to access or identify (i.e. in remote areas), drone operators may wish to contact other airspace users directly to inform them of their planned operations (e.g. local charter flight companies).

Establishing safe locations for take-off and landing & identifying obstructions

Experience suggests that extensive site reconnaissance prior to flight operations allows obstructions to be identified and increases the chances of successful data capture. Given this, we strongly advise a 'virtual' site assessment prior to fieldwork using freely available map services such as Google Earth (https://earth.google.co.uk/) or apps such as Altitude Angel (https://www.altitudeangel.com/). Google Earth's terrain layer or an alternative local terrain model (e.g. Shuttle Radar Topography Mission 90 m resolution DEM) can be used to understand local topography. These pre-flight activities will reveal some hazards, but problems posed by objects such as varying tree heights and overhead pylons will be difficult to identify. Therefore, exploring the proposed area of flight operations and beyond (to allow for unexpected deviations) later by foot will give the drone operator a more complete idea of which altitudes are safe to fly and the location of hazards should an alternative flight scenario arise. In addition, a site risk assessment is often conducted and will help identify such hazards.

Other airspace users should also be considered, and an air navigation chart can be used to assist with flight planning. When planning work in remote areas we advise that this stage should be undertaken when in reach of Internet connectivity, caching (storing) maps within flight planning software for offline usage within the field. The requirements of the chosen aircraft also need to be considered. Fixed wing systems require larger, flatter areas for take-off and landing in comparison to multi-rotor systems capable of vertical take-off and landing (VTOL). Fixed wing aircraft typically glide to a descent, requiring tens of metres of flat landing space to ensure incident-free landing although alternative retrieval techniques such as parachutes and nets (e.g. Williams et al. 2016) reduce the requirement for a large landing area and in our own practice have found parachute landings greatly facilitate the safe retrieval of fixed wing drones. The covering and stability of the landing surface should also be considered. A landing pad (Fig. 2) can help to provide a stable surface for landing multi-rotor systems and to reduce generation of dust by downdraft. Alternatively, a member of the team (other than the remote pilot) could use appropriate personal protective equipment to catch the aircraft during landing.

Insight gained through flights above rainforest canopies show that pre-flight assessments may not reveal all of the potential risks. In areas with dense tree canopies, small hills and topographic ridges may exist that are not easily identifiable from pre-flight efforts. Emergent trees can reach up to 70 m above ground level in some ecosystems, presenting themselves as obstructions of varying heights. In these circumstances it is advisable to first perform a flight over the area of interest at an appropriate altitude to avoid such obstructions and then examine the image data in the field to determine whether flying lower is safe. Quickly carrying out a first flight like this using a multi-rotor, allowing the aircraft to hover parallel to the obstructions, can provide a fast way to obtain their altitude.

International, regional and local legislation

Scientific drone operators must consult the legislation regulating drone operations in the country of intended use. DeBell et al. (2015) provide useful guidance on general operational protocols and provide details of the legislative complexity, stating 'there is a huge diversity in the legislative framework governing unmanned aerial vehicle (UAV) use globally, and coupled with diverse cultural attitudes to UAVs this can make the decision of where and how to fly quite difficult'. Some countries have established rules of operation (e.g. UK, USA, Canada, Australia) and others have no restrictions or regulations (e.g. Guinea Bissau). It may be difficult to establish what rules and regulations exist for a particular country and so as a starting point we recommend consulting community collated information which can be found at https://www.droneregulations.info. Along with the need for landowner's permission, authority for airspace usage is often required. From experience we have found that engaging with local groups and/or partnering with them has enabled smoother drone deployments with reduced concern from local communities (e.g. in Greece, we liaised with a local conservation agency who negotiated airspace use on our behalf). Regardless of the country, it is important to contact local authorities when flying close to military areas or airfields, even for countries with no drone legislation. For example on Ascension Island, where no formal restrictions exist, we had to submit pilot identification and comprehensive flight plans to local authorities 2 months prior to flights and constant contact with a local ATC had to be maintained during the fieldwork. With all locations it is critical to perform a pre-deployment check of the permitted radio frequencies (e.g. 433 MHz, 915 MHz, 2.4 GHz or 5.8 GHz etc.) and power settings for radio transmissions, as these can vary according to regulatory jurisdictions.

Flight operations

Once the appropriate pre-flight checks and permissions have been sought, a robust field procedure should be followed, for which Cunliffe et al. (2017) provide advice and an operations manual for other users to use as a guide. Importantly the operational procedure outlined therein should be modified according to the specific aircraft being used and methodology being followed. We have found that it is useful to have a prior-agreed operational protocol, with one pilot-in-command and a 'spotter/ground control station operator' to assist. Drone pilots are strongly advised to maintain their own comprehensive flight logs, as a record of both deployments and experience; such records can prove invaluable when presenting

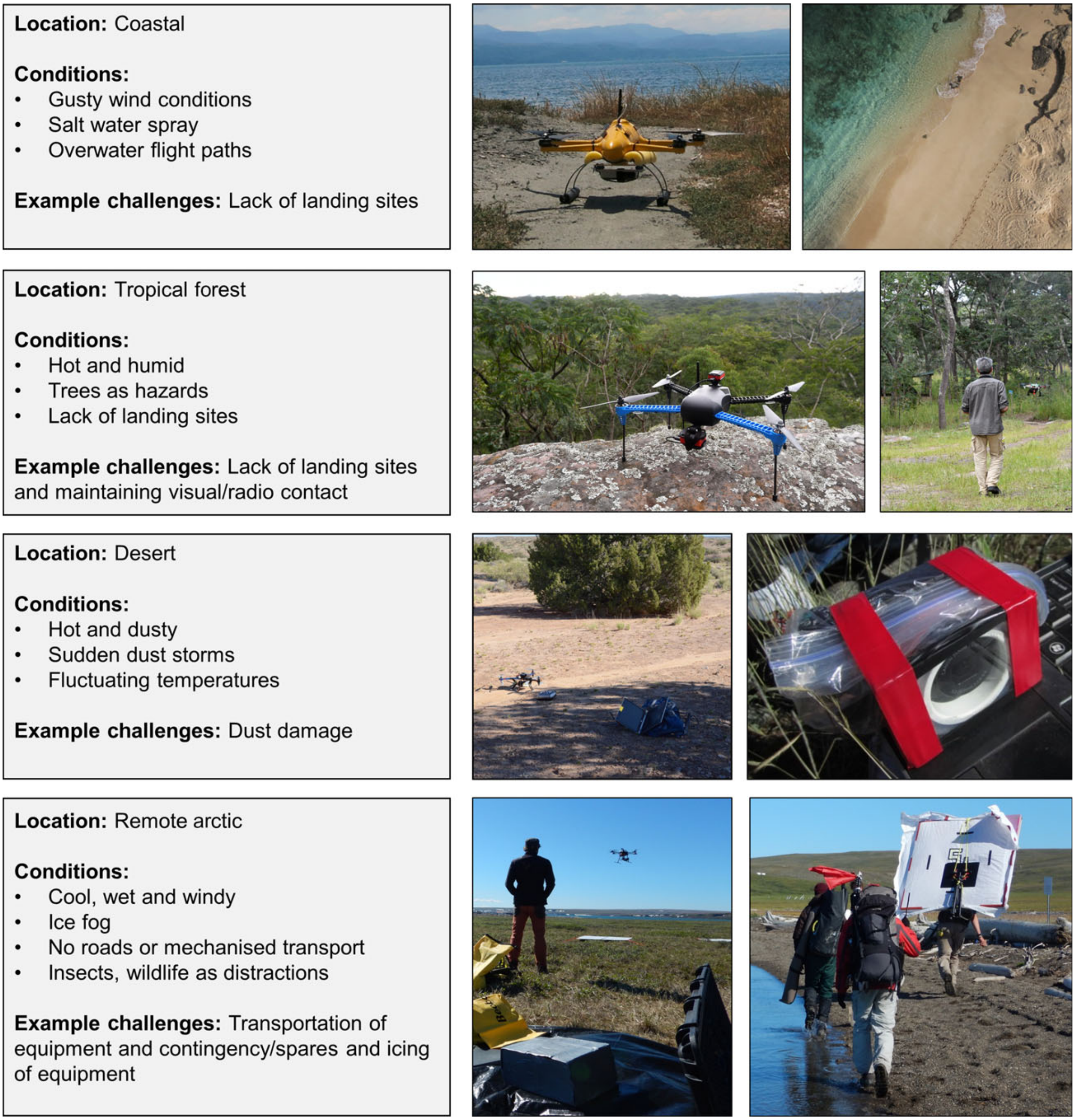

Figure 2. The challenges of drone fieldwork in four key environments.

a safety case to institutions, regulators, collaborators and landowners. This can be achieved manually or using third party services such as AirData UAV (DJI specific; https://airdata.com/).

Site-specific flight planning considerations

Specific operational issues can arise in particular settings such as coastal or over-water, forest or in remote regions. Planning operations at coastal sites is challenging since it can often be hard to find (and then access) a suitable take-off and landing area. For example in recent fieldwork in the UK Scilly Isles, it was necessary to transfer equipment from a ship to an island using a small dinghy. Alternatively, launching from land may not be feasible for some missions, and therefore boat-launches can be used as an alternative. Managing drone operations from the deck of a moving boat can be very challenging, but not impossible; there is evidence of success in achieving this (e.g. Casella et al. 2016; Christiansen et al. 2016; Williams et al. 2016). From our own experience with Pixhawk flight controllers (https://pixhawk.org/), it is necessary to perform the drone's pre-flight accelerometer and compass calibration on stable ground before deploying from the boat (which wobbles, disrupting the normal pre-flight calibration procedure of flight control sensors). Failure to do this can result in the loss of aircraft control shortly after take-off as it is likely to crash into the water. This was the case during our work in Greece, where a drone and on-board sensor were downed after an attempted boat launch. However, it is important to note that calibration procedures can vary between different flight systems.

In tropical rainforest settings, where drone-based data can provide information about forest structure, for example (Zahawi et al. 2015; Kachamba et al. 2016), and biodiversity (Van Andel et al. 2015), it is often difficult to identify sufficiently large areas for fixed wing drones to land. Fixed wing systems in these areas are generally preferred over multi-rotors because they provide greater areal coverage necessitating that flights often start and end from the edge of forest blocks, utilising openings in the canopy (Fig. 2). Where forest blocks are large, often only the edge of the forest can be surveyed which may bias observations. If flights have to be made within visual line-of-sight (VLOS), a pilot standing at the edge of a wall of trees will have very limited VLOS, thus limiting the area that can be surveyed. Dense forest canopies can also impede the transmission of Global Navigation Satellite System (GNSS) signals to the drone, and radio signals between the drone and the ground controllers due to the vegetation attenuating and/or scattering the radio signal. The impact of the vegetation is also dependent upon the geometry of communications link and the vegetation and so it can vary in space and time (e.g. Ndzi et al. 2012).

Most lightweight drones now contain positional receivers to guide the drone during automatic flight and to provide a failsafe if the radio link with the remote pilot is broken, but in high latitude environments this can cause operational issues. At high latitudes some drone operators have reported difficulties with obtaining positional lock, caused by poor visibility of geostationary equatorial GNSS satellites and issues with magnetometers and gyroscopes on-board the drone (Jensen and Sicard 2010; Williams et al. 2016). By default, some flight controllers require a minimum number of satellite GNSS connections or 'fixes' which provide a minimum accuracy of positional data (lock) before they allow take off. Obtaining a 'lock' can be difficult when the horizon is obscured, for example when working in small spaces in forests. These restrictions can be overridden by the operator on many drone systems, where appropriate, but it is useful to anticipate this potential issue and a method to resolve it in the field. In the future we expect these issues to reduce as the constellations of GNSS increase. The ability to operate drones in flight modes relying on magnetometers can be severely hampered when close to magnetic poles and manual flight may be the only option in such environments. Note, that while conducting ~200 flights at 70°N 139°W in the Canadian Arctic where the inclination of the magnetic field was ~84°, we never encountered problems with the GNSS lock but did occasionally encounter errors with magnetometers and gyroscopes.

In remote settings (e.g. polar regions and deserts), drone-based operations can also be challenging due to reduced airspace control. Less formal control does not necessarily mean that there will not be air traffic. For example for Arctic field sites aircraft are the main method of access and lightweight drones can pose major risks to other air users. Thus, establishment of lines of communication with local pilots may be required to maintain airspace safety. In addition when operating in extreme or remote conditions we plan the flight missions to start at the furthest survey point away from base camp and finish close to base camp (i.e. the flight follows a transect of some sort). This provides extra security for landing in an emergency due to battery issues as drones may otherwise land in a location where recovery is difficult. Depending on the drone pilot's preference and regulator requirements, a 'kill-switch' or sequence of commands can be programmed, so that the motors can be shut down in the event of an imminent collision with other airspace users.

Weather and Local Environment Considerations

Whilst weather forecasts can be useful for choosing optimal times for drone surveys, it is always necessary to check weather conditions at the site on arrival, particularly wind and be aware that they can change. For wind, we suggest carrying a handheld anemometer to check that wind conditions are within operational ranges, for example maximum permissible wind speed including gusts of 13.4 m s^{-1} is recommended for a 3DR Y6 hexacopter (Cunliffe et al. 2017).

In many environments, drone operators must be mindful of complex wind profiles and these can occur in all types of terrain. Our flight operations in the Arctic have been constrained by weather, especially by high wind speeds. At the coast complex winds can arise from sea breezes (land/ocean temperature differences) or from topographic landforms that alter air flow. Similar complex and localized wind effects can occur in tree canopies. When operating drones from clifftops we have encountered atmospheric turbulence (wind shear) which affects launch and landing procedures. Resultantly we have adopted a methodology where we fly high and inland over the cliff edge before bringing the drone down to a pre-identified safe landing area some distance from the cliff edge. For coastal surveys, we sometimes supplement drones with kites as part of our contingency – in high winds a single-line kite can be used to carry a camera to perform some survey tasks, although variable flying height can degrade data reproducibility (Duffy and Anderson 2016).

When working in the Chihuahuan desert (USA), we have experienced extreme localized heating of the ground surface, giving rise to rotating columns of high-intensity wind, known as dust devils. These can interfere catastrophically with drone flight operations, but are often visible when approaching survey areas. Such encounters reinforce the value of utilising a spotter to support the remote pilot in monitoring the environment (Cunliffe 2016). When working at altitude, one must also consider issues relating to air density, a factor that is fundamental to the flight operation of all aerial vehicles (air density is inversely related to both altitude and air temperature). In the Chihuahuan desert, we were flying 1800 m above sea level, with ground level air temperatures exceeding 45°C. Here, we observed that the performance envelope of multirotor aerial vehicles was affected, reducing flight endurance, manoeuvrability and payload capacity. Such issues should be considered when planning flights at high altitude sites.

Working in tropical and coastal areas with drones carries specific risks as the humidity of these environments is often high and there is a need to ensure that all electronic components stay dry. Sensors can be stored or housed in watertight cases with a desiccant, but this is often not a feasible for the drone itself. In tropical environments, areas of open canopy are often less humid and remaining in these locations can help avoid the negative effects of humidity. Foam and/or glue on components may start to become soft in hot environments, which might compromise the integrity of sensors and/or aircraft. This may be exacerbated if the aircraft has low albedo and/or exposed to direct sunlight. In these cases we advise covering the drone and components with a white textile or reflective material before arming and initiating the flight.

Dust, Damage and Redundancy

A common difficulty when operating drones is the ingress of small particles into moving parts of both aircraft and sensors, which can accelerate mechanical erosion of moving parts and damage sensors (Cunliffe 2016). We have encountered these difficulties most severely in dryland ecosystems and sandy beaches. Drylands typically have high levels of dust due to low levels of soil cohesion and vegetation cover, which are exacerbated when undertaking near-ground operations with multi-rotor aircraft (Wadcock et al. 2008; RAF, 2011). Working in the Chihuahuan desert, we destroyed several lightweight cameras due to dust ingress into lenses, prior to arriving at a low-tech solution (Fig. 2) whereby cameras were sealed inside dust-proof enclosures. At the coast, exposed electronics (e.g. motors, cable connectors and ports) can be easily clogged or corroded by sand and salt and good maintenance of drone equipment post-flight becomes very important. Possible mitigation strategies to overcome these difficulties include: (i) using landing pads to minimize generation of dust during take-off and landing operations with multi-rotor drones; (ii) cleaning moving parts after each flight, using a can of compressed air (iii) coating electronics in anti-corrosion spray and (iv) using dust-sealed cameras or other sensors (e.g. using sealed cases or ruggedized waterproof cameras such as the Canon PowerShot D30) (Fig. 2).

One critical aspect of deploying lightweight drones in any environment is the importance of contingency and redundancy in all aspects of the system. This is pertinent in very remote parts of the world, where there may be no options for obtaining replacement hardware or software (Zahawi et al. 2015). During recent fieldwork in the Canadian Arctic, we carried comprehensive sets of spare parts for all platform components; however, even this level of redundancy was not sufficient for our needs over a 2-month field campaign. As a minimum we advise drone operators to carry multiple replacement batteries (drone and controllers), a battery checker, replacement propellers, basic toolkit, soldering kit, electrical tape and cable ties. In more remote locations, there is a stringent need for the hardware (particularly airframes) to be sufficiently robust to operate in these environments and to choose the right drone(s) and sensor(s) for the operational setting. Ideally, one will have an entire fully operational drone available at the field base to provide full redundancy. This is more attainable with low-cost lightweight drone systems.

Data Quality

Spatial constraint

A key challenge with most forms of drone acquired data is that of a relatively poor spatial accuracy, as compared to, sub-decimetre spatial resolution data. The GNSS positional receivers on-board drones provide data that can be harnessed within image processing toolboxes (e.g. Cunliffe et al. 2016). However, the positional accuracy of these aircraft systems (typically ±2–10 m), is often not sufficient for some remote sensing applications and to improve the spatial accuracy of derived products, ground control markers are commonly deployed *in situ* across the scene. The locations of the markers can be independently surveyed, for example using a differential GPS to an accuracy of ca. ±0.02 m and reconstructions of the drone-sensor data can then be constrained spatially using these markers (e.g. Puttock et al. 2015; James et al. 2017). When used, markers should be designed in accordance with (i) the spatial resolution (i.e. being at least 6–8 pixels in diameter, James et al. 2017) and (ii) the electromagnetic sensitivity of the sensor (i.e. identifiable in all spectral bands, particularly when working with non-visible spectrum data). However, markers can be time-consuming to deploy, and cannot be used in all locations, such as dense forests. As we write, new GNSS systems are becoming increasingly available for drones which can yield higher precision estimates of the drone position as it flies, for example Real Time or Post Processing Kinematic (RTK or PPK) GNSS systems. While uptake of these systems has not yet been widespread, we anticipate that within a few years these may replace current methodologies employing *in situ* markers, although we advise that independent ground validation should remain a critical requirement for remote sensing investigations. Furthermore, newer low-cost receivers support recording of raw GNSS observations (if base stations are close) that can be post-processed to improve accuracy for incorporation into any data product, but this capability often needs to be enabled prior to any flights taking place.

Shadows and sun angle effects

It is generally preferable to collect data when illumination conditions are relatively consistent. In any areas with structured surfaces, for example those covered by vegetation or with coarse sediment, there may be issues associated with temporally variant shadows. When working in dryland ecosystems, for example the vegetation cover is commonly spatially discontinuous and feature matching algorithms can be confused by inconsistent shadows between images (Carrivick et al. 2016), particularly where the bare soils have high albedo. To minimize changes in shadows between different images, it can be useful to undertake aerial surveys close to solar noon, thus minimising shadows and significant changes in illumination angles (Puttock et al. 2015; Cunliffe et al. 2016; MicaSense, 2017). In polar regions, even at solar noon, sun angles are usually low, potentially requiring drone operators to experiment with varying exposure settings on sensors to optimize image quality. For example flying on days with variable cloud cover can lead to changes in illumination in imagery, thus influencing the homogeneity of spectral signatures influencing derived spectral, structural or classification-based data products.

Artefacts caused by the reflectance of light from water-based surfaces have been a long-standing issue in remote sensing data products created from visible spectrum satellite and airborne sensors (Kay et al. 2009). A detailed explanation about the occurrence of sunlight or skylight glitter on surface waters (often referred to as glint) in aerial photography, its geometry manifestations and distributions can be found in Cox and Munk (1954) and Aber et al. (2010). In any data collection scenario over water bodies, the drone operator must be mindful of such issues, because they manifest themselves in complex forms in fine-grained data (Fig. 3A). During fieldwork in the Maldives when using drones to map coral reefs (i.e. attempting to view through the water), we found sun glint issues caused major problems with image data quality (Fig. 3A). Capturing image data when the sun is lower on the horizon (avoiding midday sun) (as suggested by Casella et al. 2016 and Hodgson et al. 2013) helped us to achieve data through water free of sun glint. We also programmed the drone to always point the camera north, so that whilst following a typical 'lawnmower' flight pattern, the impact of glint on the sensor data was minimized as the viewing zenith was approximately 90 degrees to the sun. In addition to sun glint, disturbance to the water's surface (i.e. caused by boats) was an issue during our work in the Amvrakikos Gulf, Greece (Fig. 3B). Careful timing of flights can aid in minimising these issues.

Wind and motion blur

In areas with high wind, movement of features of interest (e.g. vegetation), can cause problems with feature matching between images. Vegetated sand dunes (Fig. 3C) are an ecosystem where vegetation movement is a particular issue. Beyond environmental conditions, movement in the sensor gimbal or the sensor itself during data capture can lead to motion blur in imagery influencing data quality. Poorly designed or fitted camera mounts/gimbals may exacerbate problems with motion blur from wind buffeting of aircraft, due to insufficient vibration dampening and movement of the sensor during flight. Where applicable, to avoid/reduce motion blur, shutter speeds of optical sensors should be set with consideration of the intended speed of the aircraft (i.e. higher speeds require a faster shutter). We recommend planning test flights to assess such issues with initial assessment of data quality in the field. Changing to a fixed mount and/or altering camera mounts and orientations (i.e. reducing aerodynamic drag) may help to solve such issues. This approach was needed whilst working in constant wind speeds of 10 m s^{-1} on Ascension Island.

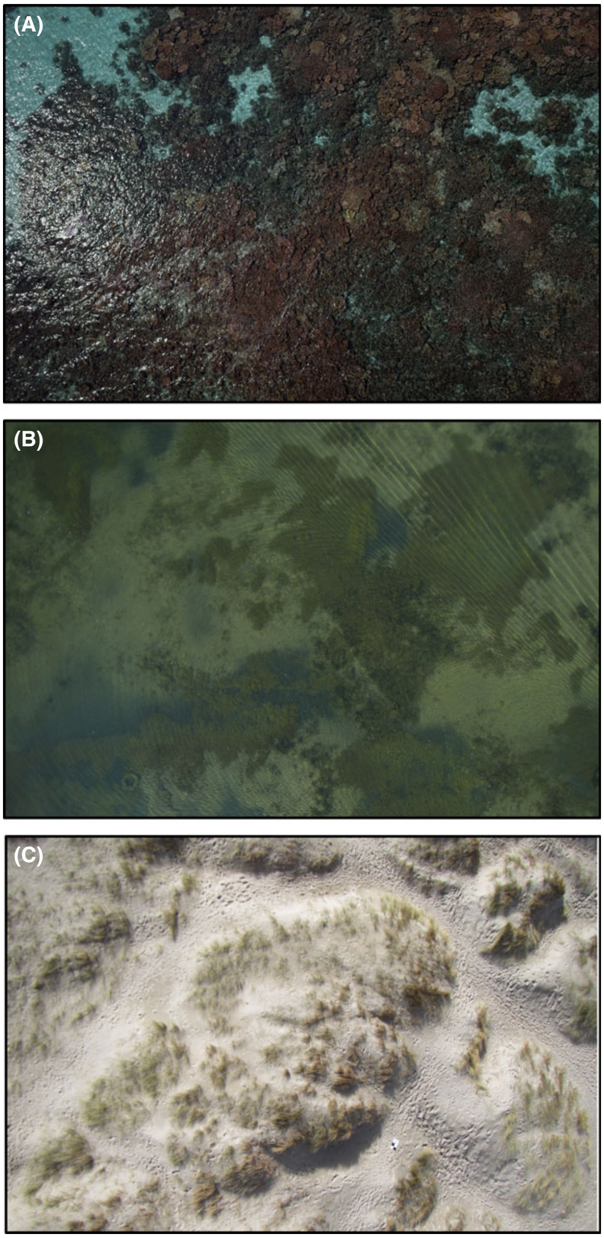

Figure 3. Issues with optical imaging. (A) Sun glint over coral reefs in the Maldives, (B) ripples in the water's surface caused by a boat in Greece and (C) Marram grass moved by wind on sand dunes in the UK.

Conducting flight operations during low wind conditions will help to mitigate both of these issues, but workflows for data analysis may need to address variable data quality. Software tools such as PixelPeeper (https://pixelpeeper.com/) allow for the screening of data, aiding in the removal of images that are likely to introduce error further into the processing workflow (e.g. blurry photographs).

Batteries

Most lightweight drone systems used for environmental research are powered by lithium polymer (LiPo) batteries, which represent one of the most troublesome and potentially hazardous components of drone operations (Scrosati et al. 2001; Salameh and Kim 2009). The overriding issue here is that LiPo's represent a significant fire risk, particularly if they are (i) over-(dis)charged, (ii) (dis)charged too rapidly, or (iii) the physical integrity of the cells is compromised. Because of this fire risk, the transportation of LiPos is strictly regulated. For transport by air, the International Civil Aviation Organization (ICAO) determines these regulations, and many state jurisdictions impose additional controls on the transportation of LiPos under dangerous goods regulations (e.g. Canada). ICAO currently prohibits the transport of Lithium ion batteries as cargo on passenger aircraft, although LiPos within passenger luggage are still permitted within strict limits. But these restrictions can preclude the transport of LiPos above a certain size (currently determined by watt hours (Wh) or lithium content), which can impede field deployments, particularly with larger drone systems.

LiPo batteries are a relatively expensive component in drone systems, and do have a finite lifespan (Salameh and Kim 2009) and there is often a degree of reluctance by users towards replacing older, less effective LiPos. Older LiPos can pose a safety issue, particularly when undertaking endurance flight operations. Users are strongly encouraged to keep logs for individual batteries, to allow declining battery performance to be monitored; such recording is commonly also mandated by regulators. For safe storage and transport, we suggest that LiPos be (dis) charged to 50–60% and placed within individual fire-resistant bags. Damaged LiPos should never be transported and should be safely disposed of as soon as possible. We have used a lightbulb to assist in full discharge when operating in remote areas. To ensure the long life and stability of cells, they should be charged with a balance charger, and a maximum charge rate of 1C is recommended (i.e. maximum charge rate of 5 A for a 5000 mAh battery). LiPo efficacy is usually impeded when cell temperatures are below 0°C (Salameh and Kim 2009), and we have observed problems with sudden voltage drops in flight when using LiPos that have not been adequately warmed; ideally above approximately 10°C prior to use. It is essential to plan for the charging requirements of LiPos, especially when travelling to remote places. For example low voltage photovoltaic arrays may not be adequate to charge LiPos comprising of many cells.

Social and Ethical Considerations, Challenges and Mitigation

Until this point, we have considered some of the challenges relating to deploying drones in particular physical environments, and the equipment itself. However, it is important also to consider the social environment within which drones are deployed, and the associated challenges and opportunities, especially given ethical assessment increasingly required in scientific research. In some circumstances the use of drones can have positive influences on people, for example by empowering local people to monitor their resources more effectively (Paneque-Gálvez et al. 2014) or by fostering improved relationships with stakeholders through conversations around the drones themselves and associated visually attractive data products. However, there are several ways in which drones may cause real or perceived harm to people, which can in turn create difficulties for drone users. Here we first identify some of the possible social and ethical challenges that can exist, and then identify possible strategies to mitigate these challenges.

A range of potential social challenges associated with using drones are detailed in Table 2, many of which have been identified previously (e.g. Boucher 2015; Klauser and Pedrozo 2015; Sandbrook 2015). If not appropriately mitigated, these challenges can lead to conflict. Such conflicts could result in damage to equipment and/or undermine stakeholder relations, impacting or undermining the wider scientific or applied objectives of the work.

We now provide suggestions to help mitigate the potential social challenges identified in Table 2, based on a combination of reviewed literature, the experience of the authors, and common sense.

First, it is essential to recognize that social problems might occur. A recent review of the published literature on the use of drones for conservation and ecology found a remarkable lack of engagement with these issues (Sandbrook 2015), although in our own experience most drone users do recognize their importance. Second, as discussed earlier, it is essential to comply with local regulations. In most jurisdictions, there will be rules regarding flying drones in proximity to people and the collection of data and these must always be obeyed.

Third, when data on humans (including their land or property) are to be collected, projects should go through a human ethics review process. Such processes are designed to identify potential problems and help researchers develop mitigation strategies. For example it may be appropriate (or mandated by law) to seek consent from key stakeholders before collecting data relating to them. It may also be necessary to think in advance about how human data will be stored and shared (e.g. will images showing illegal behaviour be shared with law enforcement authorities? What action would you take if somebody demands to see any data relating to them?). In many cases ethical reviews are already required for drone research, and we encourage universal adoption of this practice.

Finally, ensuring good communication with stakeholders is essential. In many cases problems can be avoided by

Table 2. Social concerns associated with using drones.

Nature of social interaction	Description of social challenge
Safety	In some circumstances drones could be dangerous for people on the ground, particularly if used in crowded places or at very low altitude. For this reason such usage is not legal without special permission from the national aviation authority in many jurisdictions
Disturbance	Drones can be noisy, potentially distracting or alarming for those who are not used to them. This could be dangerous (e.g. if people are operating machinery), annoying or upsetting (e.g. if they are wanting to enjoy the quiet of the natural environment).
Privacy	People may feel that drones are collecting data that violates their privacy, for example by taking photographs of them or their belongings (their home, their land, their trees, their pets etc.). This concern can occur even when no such data are being collected.
Fear	Drones can insight fear in people. This fear can be related to safety, disturbance, privacy or may just relate to a lack of familiarity with the technology. People may be afraid of drones because they associate the technology with military applications or intelligence gathering
Data access and usage	People may request or feel that they should be given access to the data collected, because it relates to them personally (e.g. images in which they feature) or regarding environmental features that were surveyed by the drones (e.g. locations of animals). They may worry that drones are being used to collect data that will be used against their interests, such as the creation of a National Park
Changing perceptions of environmental management	Flying drones to collect data about a particular environment and the wildlife therein may change perceptions about the appropriate use and management of that environment. For example collecting data about a dangerous animal may lead to people assuming that those using the drones should be responsible for controlling the animal. This could lead for demands for compensation and associated conflict

explaining how and why drones are being used to key stakeholders in advance. Indeed, in our experience drones (and the conversations they prompt) can underpin new opportunities for engagement and outreach, allowing for greater dissemination of scientific understanding and research findings.

Conclusions

The pace of development of both the technological and regulatory sides of drone operations makes it difficult to be overly prescriptive about how to successfully undertake drone operations. The peer-reviewed literature often fails to capture the finer details of methodology such as how to prepare for and overcome issues that affect safety or data capture. Scientists should not underestimate the wealth of knowledge available in the ‘grey literature’ and from on-line forums: although these ‘hobbyist’ sites can be easily regarded as being separate to scientific operations, they have provided us with great insight when pioneering new drone deployments in challenging places (we credit the helpful community that reside in DIYdrones.com with much that we have learned). Here, we have provided practical advice aimed at increasing the success of any environmental scientist, ecologist or conservation practitioner wishing to use drones for research purposes, especially in more challenging environmental settings. We believe careful consideration of the issues raised herein will promote the success of drone-based research applications both with regards to data collection and the social perceptions of such research.

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References

Aber, J., I. Marzolff, and J. Ries. 2010. *Small-format aerial photography*. Elsevier, Amsterdam.

Aurbach, D., Y. Talyosef, B. Markovsky, E. Markevich, E. Zinigrad, L. Asraf, et al. 2004. Design of electrolyte solutions for Li and Li-ion batteries : a review. *Electrochim. Acta* **50**, 247–254. https://doi.org/10.1016/j.electacta.2004.01.090.

Boucher, P. 2015. Domesticating the drone : the demilitarisation of unmanned aircraft for civil markets. *Sci. Eng. Ethics* **21**, 1393–1412. https://doi.org/10.1007/s11948-014-9603-3.

Bukart, A., V. L. Hecht, T. Kraska, and U. Rascher. 2017. Phenological analysis of unmanned aerial vehicle based time series of barley imagery with high temporal resolution. *Precis. Agric.* https://doi.org/10.1007/s11119-017-9504-y.

Carrivick, J. L., M. W. Smith, and D. J. Quincey. 2016. *Structure from motion in the geosciences*. Wiley-Blackwell, Chichester.

Casella, E., A. Collin, D. Harris, S. Ferse, S. Bejarano, V. Parravicini, et al. 2016. Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. *Coral Reefs* **36**, 269–275. https://doi.org/10.1007/s00338-016-1522-0.

Christiansen, F., A. M. Dujon, K. R. Sprogis, J. P. Y. Arnould, and L. Bejder. 2016. Noninvasive unmanned aerial vehicle provides estimates of the energetic cost of reproduction in humpback whales. *Biosphere* **7**, e01468.

Christie, K. S., S. L. Gilbert, C. L. Brown, M. Hatfield, A. Biology, A. Fairbanks, et al. 2016. Unmanned aerial systems in wildlife research: current and future applications of a transformative technology. *Front. Ecol. Environ.* **14**, 241–251. https://doi.org/10.1002/fee.1281.

Cox, C., and W. Munk. 1954. Measurement of the roughness of the sea surface from photographs of the sun’s glitter. *J. Opt. Soc. Am.* **44**, 838. https://doi.org/10.1364/JOSA.44.000838.

Cunliffe, A. M. 2016. *Understanding structure and function in semiarid ecosystems: implications for terrestrial carbon dynamics in drylands*. University of Exeter, Exeter.

Cunliffe, A. M., R. E. Brazier, and K. Anderson. 2016. Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry. *Remote Sens. Environ.* **183**, 129–143. https://doi.org/10.1016/j.rse.2016.05.019.

Cunliffe, A. M., K. Anderson, L. Debell, and J. P. Duffy. 2017. A UK Civil Aviation Authority (CAA) -approved operations manual for safe deployment of lightweight drones in research. *Int. J. Remote Sens.* **38**, 2737–2744. https://doi.org/10.1080/01431161.2017.1286059.

DeBell, L., K. Anderson, R. E. Brazier, N. King, and L. Jones. 2015. Water resource management at catchment scales using lightweight UAVs : current capabilities and future perspectives. *J. Unmanned Veh. Syst.* **30**, 7–30.

Ditmer, M. A., J. B. Vincent, L. K. Werden, J. C. Tanner, T. G. Laske, P. A. Iaizzo, et al. 2015. Bears show a physiological but limited behavioral response to unmanned aerial vehicles. *Curr. Biol.* **25**, 1–6. https://doi.org/10.1016/j.cub.2015.07.024.

Duffy, J. P., and K. Anderson. 2016. A 21st-century renaissance of kites as platforms for proximal sensing. *Prog. Phys. Geogr.* **40**, 352–361. https://doi.org/10.1177/0309133316641810.

Hodgson, J. C., and L. P. Koh. 2016. Best practice for minimising unmanned aerial vehicle disturbance to wildlife in biological field research. *Curr. Biol.* **26**, R404–R405. https://doi.org/10.1016/j.cub.2016.04.001.

Hodgson, A., N. Kelly, and D. Peel. 2013. Unmanned aerial vehicles (UAVs) for surveying Marine Fauna: a dugong case study. *PLoS ONE* **8**, e79556. https://doi.org/10.1371/journal.pone.0079556.

Husson, E., O. Hagner, and F. Ecke. 2014. Unmanned aircraft systems help to map aquatic vegetation. *Appl. Veg. Sci.* **17**, 567–577. https://doi.org/10.1111/avsc.12072.

Husson, E., F. Ecke, and H. Reese. 2016. Comparison of manual mapping and automated object-based image analysis of non-submerged aquatic vegetation from very-high-resolution UAS images. *Remote Sens.* **8**, 724. https://doi.org/10.3390/rs8090724.

James, M. R., S. Robson, S. Oleire-oltmanns, and U. Niethammer. 2017. Optimising UAV topographic surveys processed with structure-from-motion : ground control quality, quantity and bundle adjustment. *Geomorphology* **280**, 51–66. https://doi.org/10.1016/j.geomorph.2016.11.021.

Jensen, A., and J. Sicard. 2010. "Coordinates : a resource on positioning, navigation and beyond". Challenges for positioning and navigation in the Arctic. Available at: http://mycoordinates.org/challenges-for-positioning-and-navigation-in-the-arctic (accessed 1 January 2017).

Kachamba, D. J., H. O. Ørka, T. Gobakken, T. Eid, and W. Mwase. 2016. Biomass estimation using 3D data from unmanned aerial vehicle imagery in a tropical woodland. *Remote Sens.* **8**, 1–18. https://doi.org/10.3390/rs8110968.

Kay, S., J. D. Hedley, and S. Lavender. 2009. Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths. *Remote Sens.* **1**, 697–730. https://doi.org/10.3390/rs1040697.

Klauser, F., and S. Pedrozo. 2015. Power and space in the drone age : a literature review and politico-geographical research agenda. *Geogr. Helv.* **70**, 285–293. https://doi.org/10.5194/gh-70-285-2015.

Koh, L. P., and S. A. Wich. 2012. Dawn of drone ecology : low-cost autonomous aerial vehicles for conservation. *Trop. Conserv. Sci.* **5**, 121–132. https://doi.org/WOS:000310846600002.

Long, N., B. Millescamps, B. Guillot, F. Pouget, andX. Bertin. 2016. Monitoring the topography of a dynamic tidal inlet using UAV imagery 1–18. https://doi.org/10.3390/rs8050387.

MicaSense. 2017. Best practices: collecting data with MicaSense RedEdge and parrot sequoia. Available at: https://support.micasense.com/hc/en-us/articles/224893167-Best-practices-Collecting-Data-with-MicaSense-RedEdge-and-Parrot-Sequoia (accessed 3 July 2017).

Ndzi, D. L., L. M. Kamarudin, E. A. A. Mohammad, A. Zakaria, R. B. Ahmad, M. M. A. Fareq, et al. 2012. Vegetation attenuation measurements and modelling in plantations for wireless sensor network planning. *Prog. Electromagn. Res. B* **36**, 283–301.

Nedjati, A., B. Vizvari, and G. Izbirak. 2016. Post-earthquake response by small UAV helicopters. *Nat. Hazards* **80**, 1669–1688. https://doi.org/10.1007/s11069-015-2046-6.

Paneque-Gálvez, J., M. K. Mccall, B. M. Napoletano, S. A. Wich, and L. P. Koh. 2014. Small drones for community-based forest monitoring: an assessment of their feasibility and potential in tropical areas. *Forests* **5**, 1481–1507. https://doi.org/10.3390/f5061481.

Pomeroy, P., L. O. Connor, and P. Davies. 2015. Assessing use of and reaction to unmanned aerial systems in gray and harbor seals during breeding and molt in the UK. *J. Unmanned Veh. Syst.* **113**, 102–113. https://doi.org/10.1139/juvs-2015-0013.

Puttock, A., A. M. Cunliffe, K. Anderson, and R. E. Brazier. 2015. Aerial photography collected with a multirotor drone reveals impact of Eurasian beaver reintroduction on ecosystem structure. *J. Unmanned Veh. Syst.* **3**, 123–130. https://doi.org/10.1139/juvs-2015-0005.

RAF. 2011. Making landings safer. Available at: http://www.raf.mod.uk/news/archive.cfm?storyid=DFF79349-5056-A318-A8DBA7DB432A0454.

Salameh, Z. M., and B. G. Kim. 2009. Advanced lithium polymer batteries, in Power & Energy Society General Meeting, 2009. PES '09. IEEE. IEEE. https://doi.org/10.1109/pes.2009.5275404

Sandbrook, C. 2015. The social implications of using drones for biodiversity conservation. *Ambio* **44**, 636–647. https://doi.org/10.1007/s13280-015-0714-0.

Scrosati, B., F. Croce, and S. Panero. 2001. Progress in lithium polymer battery R & D. *J. Power Sources* **100**, 93–100.

Smith, M. W., J. L. Carrivick, and D. J. Quincey. 2015. Structure from motion photogrammetry in physical geography. *Prog. Phys. Geogr.* **40**, 1–29. https://doi.org/10.1177/0309133315615805.

Van Andel, A. C., S. A. Wich, C. Boesch, and L. P. I. N. Koh. 2015. Locating chimpanzee nests and identifying fruiting trees with an unmanned aerial vehicle. *Am. J. Primatol.* **77**, 1122–1134. https://doi.org/10.1002/ajp.22446.

Vas, E., A. Lescroël, O. Duriez, G. Boguszewski, and D. Grémillet. 2015. Approaching birds with drones : first experiments and ethical guidelines. *Biol. Lett.* **11**, 20140754.

Wadcock, A. J., L. A. Ewing, E. Solis, M. Potsdam, and G. Rajagopalan. 2008. Rotorcraft Downwash Flow Field Study to understand the aerodynamics of helicopter brownout. Pp. 1–27 *in* American helicopter society southwest region technical specialists meeting, technologies for the next generation of vertical lift aircraft.

Williams, G. D., A. D. Fraser, A. Lucieer, D. Turner, E. Cougnon, P. Kimball, et al. 2016. Drones in a cold climate. Available at: https://eos.org/project-updates/drones-in-a-cold-climate (accessed 24 March 2017).

Zahawi, R. A., J. P. Dandois, K. D. Holl, D. Nadwodny, J. L. Reid, and E. C. Ellis. 2015. Using lightweight unmanned aerial vehicles to monitor tropical forest recovery. *Biol. Conserv*. **186**, 287–295. https://doi.org/10.1016/j.biocon.2015.03.031.