Work Package 2: Technological Innovation for Sustainable Development

Deliverable T2.1.1: Project report

Applications of Drone Technology for Sustainable Development of the Coastal Zone: A Literature Review

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SUSTAINABLE RESILIENT COASTS

Project Partners

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Executive Summary

Coastal zones are at the frontline of sustainability challenges arising from the exploitation of natural resources. Integrated coastal zone management (ICZM) seeks to address these challenges by balancing multiple, and sometimes conflicting, objectives within the limits set by natural dynamics. To do so effectively requires a reliable evidence-base upon which decision makers, such as policymakers and planners, can make informed management decisions. Data and information obtained from modern drone technology can help. This report explores the practical applications of drone technology for ICZM and examines the relevance of the technology to the UN Sustainable Development Goals (SDGs) at the coast. It has been produced as part of the EU-funded Sustainable Resilient Coasts (COAST) project, a collaboration between partners from Iceland, Finland, Ireland and Northern Ireland focusing on the future challenges and development of coastal areas in Europe's Northern Periphery and Arctic (NPA) region. The project seeks to deliver practical guidance for coastal local authorities to support resilience building and coastal sustainability. This document is therefore intended to educate local authorities with limited experience but a desire to understand the capabilities of drone technology for ICZM and sustainable development.

The potential for drones to contribute data and information to support ICZM and sustainable development at the coast is appreciable, but has been underexplored and underutilized. This report describes a number of innovative applications of drone technology to support ICZM in nine key areas. It also explores the relevance of drone technology to the SDGs. This should be of interest to local authorities given their responsibilities in relation to coastal management and their role in contributing to the SDGs at the local level. In order to appreciate these applications, some technical background on the technology is provided, including information about different platforms, sensors, and software, as well as information related to technological limitations and logistical challenges. A dictionary of technical terms is provided in an appendix, for reference.

The range of applications described in this report, which is not exhaustive, demonstrates the potential for drone technology to support ICZM and the SDGs at the coast. Examples documented in this report include surveillance of illegal fishing and aquaculture activities, seaweed resource assessments, cost-estimation of post-storm damages, and documentation of natural and cultural heritage sites under threat from, for example, erosion and sea-level rise. An awareness of such activities, as well as the limitations of the technology, can help local authorities evaluate their options for management activities. We also highlight the need for policies or strategies that deal specifically with the use of drones for those local authorities who wish to employ them as part of their activities.

Contents

Acronyms

CAD	Computer aided design
CBD	Convention on Biological Diversity
COP21	Conference of the Parties (COP21) Paris Agreement
DSS	Decision support system
FPS	Frames per second
GIS	Geographical Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSD	Ground Sampling Distance
HAB	Harmful algal bloom
LiDAR	Light detection and ranging
MCA	Multiple criteria analysis
NDVI	Normalised difference vegetation index
NIR	Near infrared (part of the electromagnetic spectrum)
RGB	Red, green, blue (visible portion of the electromagnetic spectrum)
RPAS	Remotely piloted aircraft system
RTK	Real time kinematic
SDGs	Sustainable Development Goals
SFM	Structure from motion
SUA	Small Unmanned Aircraft
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UN	United Nations
VTOL	Vertical Take Off and Landing

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1. Introduction

With the advent of low-cost consumer grade drones, the technology has become ubiquitous amongst many organisations and institutions, including many local government agencies in North America, Oceania, and Europe (Miller, 2018; council.ie, 2019; Gee, 2019). Amongst its many uses, the technology is well-placed to support integrated coastal zone management (ICZM)[1] activities because it can deliver relevant data and information that can contribute to evidence-based decision making. Many local authorities struggle with the implementation of ICZM, due in part to limited access to resources and funding (Cummins *et al.*, 2004). The low operating cost, high level of automation, and high quality of survey data from modern drone technology can help support local authorities in their efforts to implement ICZM (Scarelli *et al.*, 2017).

Sustainability is at the heart of ICZM. The challenge for society is how to balance economic growth with environmental, social, cultural and recreational objectives, all while ensuring we can meet "the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987). This is especially challenging at the coast, where populations and industries tend to be concentrated, often resulting in stakeholder conflicts. Drone technology can help to support sustainable development at the coast and can be used to help achieve the UN Sustainable Development Goals (SDGs) (Kitonsa and Kruglikov, 2018). Part of the 2030 Agenda for Sustainable Development (UN General Assembly, 2015), the SDGs are comprised of 17 goals that address global challenges, including those related to poverty, inequality, climate change, environmental degradation, peace and justice (Figure 1). For each goal, a number of targets have been defined, and for each target, there are a number of indicators and metrics for measuring progress towards those targets, and, ultimately, the overall goal. Unfortunately, it is difficult to quantify many of those metrics, but there are many areas where drone technology can help. These are described explicitly in this report.

Figure 1: The 17 United Nations Sustainable Development Goals.

[1] See appendix I

Everyone has a responsibility to contribute to the SDGs, including local authorities. In fact, some indicators specifically reference the actions of local government, such as indicator 13.1.3, defined as the "Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies" (UN General Assembly, 2020, p. 1). In light of such responsibilities, and the potential for drone technology to help local authorities work toward the SDGs, we believe this report is timely.
Complementing the SDGs are other global initiatives, including the Convention on Biological Diversity (CBD) (United Nations, 1992), the Sendai Framework for Disaster Risk Reduction (United Nations, 2015b), and the Conference of the Parties (COP21) Paris Agreement (United Nations, 2015a). The data requirements to deliver progress towards these conventions are substantial (Politi *et al.*, 2019), but drone technology can play a role in helping to deliver those requirements. This report, while focused primarily on the SDGs for the coast, highlights a number of applications where there are synergies with these international conventions.

In 2018, a workshop was held in Maine, USA on the practical uses of drones to address management problems in coastal zones. The workshop summary report concluded "[coastal] managers are eager to use drones, but how to use them is not always well understood" (Alliance for Coastal Technologies, 2018, p. 3). This report aims to de-mystify the use of drone technology for coastal management by highlighting various practical applications of the technology from around the world. It has been written specifically for local authorities, although other audiences may find it useful as an introduction to drone technology for sustainable development and management of the coastal zone (and potentially other environmentally sensitive areas). The report gives a basic introduction to different types of drone platforms, sensors, and software. It then goes on to discuss specific applications in nine key areas in which drone technologies can support ICZM and the UN SDGs at the coast (Figure 2). Definitions of technical terms are provided in appendix I, for reference, and highlighted in the text in green.

This report was produced as part of the Sustainable Resilient Coasts (COAST) project, a collaboration between partners from Iceland, Finland, Ireland and Northern Ireland focusing on the future challenges and development of coastal areas. Information from this report will be integrated into our Sustainable Resilient Coasts Toolbox for local authorities, an online resource focusing on SMART Blue Growth[2]. For more information see: http://coast.interreg-npa.eu/

[2] SMART Blue Growth refers to the sustainable growth of the marine and maritime sectors. It is based on the principles of Sustainability, Mitigation, Planning, Adaptation, Resilience and Transition (SMART).

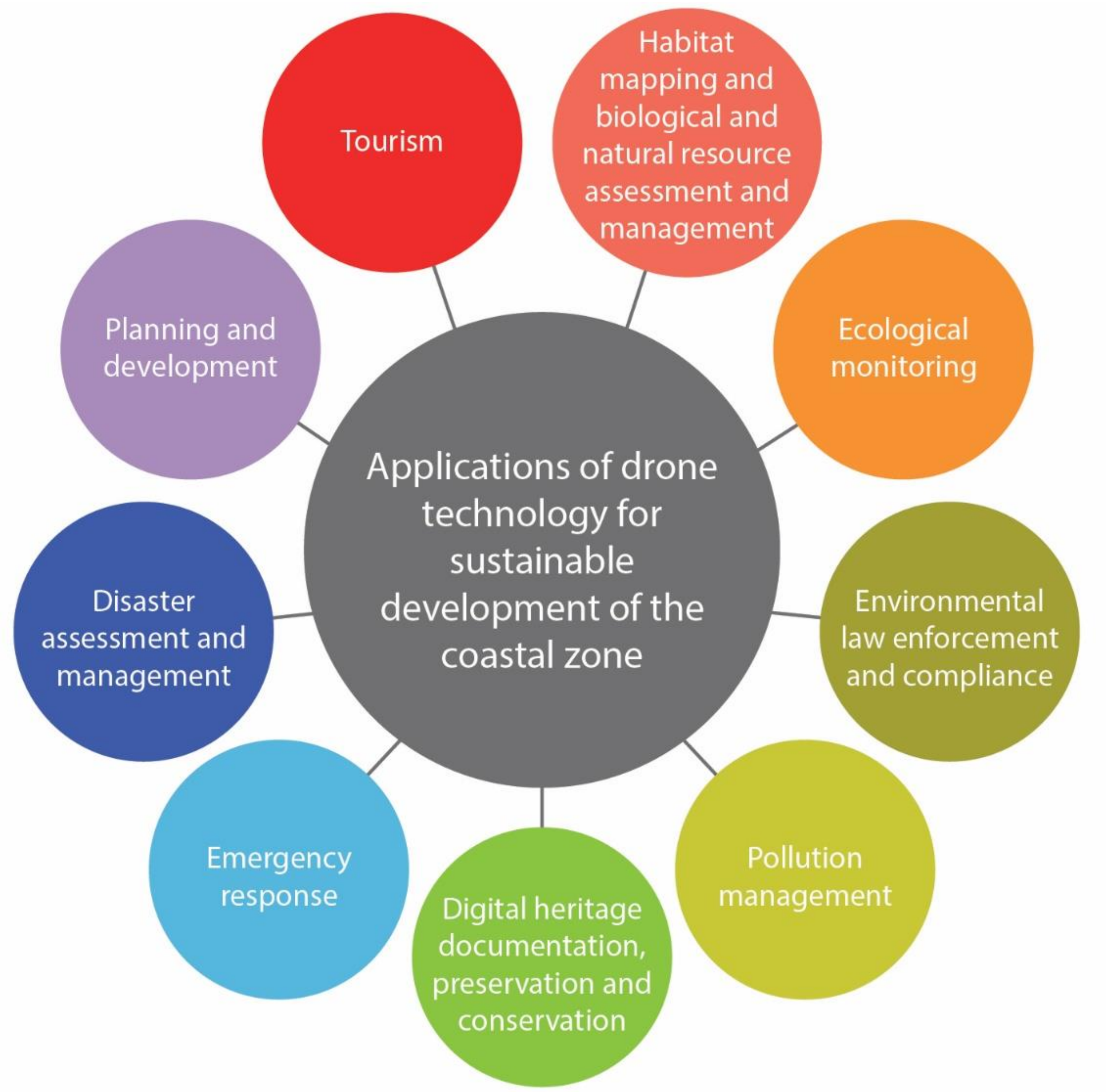

Figure 2: Nine key areas in which drone technologies can support ICZM and the UN SDGs at the coast.

2. Overview of drone technology

While there is a plethora of technical literature on different types of drones, ancillary equipment and software, it can be difficult for the non-expert to navigate this material. The following section aims to help members of local authorities with limited experience in this space to understand the basic types and capabilities of drone technologies, as well as their limitations. In this document, 'drones' refer to small, unmanned aircraft, sometimes also called unmanned aerial vehicles (UAVs), small unmanned aircraft (SUAs), unmanned aerial systems (UASs), or remotely piloted aircraft systems (RPASs)[3].

2.1 Instruments

There are many different types of drones on the market with a range of different features. Rotary wing drones consist of blades that rotate around one or more rotors, like a helicopter, to lift the aircraft. Fixed wing drones consist of rigid wings that generate lift from forward airspeed, like a traditional airplane. A key difference between the two is that rotary wing drones have the ability to hover, whereas fixed wing drones do not. It is therefore easier to control a camera or sensor mounted to a rotary wing drone. Fixed-wing drones, though, can fly faster than rotary wing drones, have longer endurance, and thus can cover larger areas.

Drones can be further subdivided into four general types of platforms (Figure 3). Multi-rotor drones are very common. These include quadcopters, hexacopters, octocopters, and many others[4]. Affordable (from c. €1,300[5]), consumer grade multi-rotor drones, such as the DJI Phantom 4 Pro, are commonly used for professional photography, video recording or visual inspection, but they can also be used for survey-grade mapping and photogrammetry, depending on the desired level of data quality (Boon *et al.*, 2017). Many of these consumer grade multi-rotor systems are designed to be easy to fly. For example, the in-built GPS in the Phantom 4 Pro helps to assist pilots fly more steadily, and in-built infrared sensors help with obstacle avoidance. More expensive systems can carry larger payloads (for example, professional video recording equipment or LiDAR sensors) and/or might include more advanced GPS capabilities. Flight time (c. 28 minutes for the Phantom 4 Pro) is a key limitation of multi-rotor drones, which are often powered by rechargeable lithium batteries.

Fixed-wing drones tend to be more expensive than multi-rotor drones, but are sometimes preferred for aerial mapping applications due to their ability to cover large areas. More inexpensive models can be adapted from hobby planes, but their assembly requires expertise. Since many fixed-wing drones use petrol engines as their power source, they can stay in flight longer than battery-operated drones. For example, the Penguin C has a flight endurance of over 20 hours. Some small fixed-wing models can be launched by hand, but larger models require a runway or catapult to launch. Because of their design, fixed-wing drones usually require more experience to fly than multi-rotor drones.

Vertical Takeoff and Landing (VTOL) drones are hybrid platforms with both fixed wings and rotors. The rotors allow the drone to take off and land vertically and hover while in the air, while the fixed wings give the added benefits of speed and endurance. These tend to be expensive and occupy niche areas, for example in academic research and professional surveying. Like fixed-wing drones, these can be difficult to operate without expertise.

Flying submersibles can be used in the air and underwater. These are relatively new, expensive, and used for niche applications, although they have obvious applications for coastal zone management (*e.g.* for inspection of aquaculture farms). Examples include the SeaHawk flying submersible product line and the SubUAS Naviator.

Drone systems themselves are comprised of a number of components. These typically include the aircraft itself, a battery (if battery powered), propellers, a gimbal (used to orientate the mounted camera or sensor), a camera or sensor, and a remote control. Most of the drones on the market can be operated with a mobile device, such as a tablet or mobile phone, or laptop equipped with data collection software (see section 2.3), connected to the remote control.

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[3] *UAS* and *RPAS* refer to the whole drone and payload system, including the gimbal and ground control

[4] Single rotor helicopters also exist, but are less common.

[5] Prices in this report are correct as of July 2020.

Figure 3: Four types of aerial drone platforms, including three types of multi-rotor systems. (a) DJI Phantom 4 Pro Quadcopter (from c. €1,300) [Source: DJI]; (b) DJI Matrice 600 Pro Hexacopter (from c. €5,699)[Source: DJI]; (c) DJI Spreading Wings S1000 Octocopter (kit from c. €4,400) [Source: DJI]; (d) senseFly eBee (from c. €22,000) [Source: senseFly]; (e) WingTra One VTOL drone (from c. €19,000) [Source: WingTra]; (f) SeaHawk D4 flying submersible [Source: SeaHawk]

Other equipment and accessories may be required. For example, for mapping and photogrammetry applications, georeferencing may be important. This is the process of assigning real world coordinates (e.g. latitude/longitude) to the imagery. Although many drones come equipped with an in-built GPS, the positional accuracy is often limited to within one to several metres. The vertical accuracy is typically lower than the horizontal accuracy. For beach monitoring, for example, this is usually insufficient. A real-time kinematic (RTK) GPS can increase positional accuracy to within millimetres, although the accuracy of processed photogrammetric models will be much lower, especially in the vertical, due to inherent errors in the bundle block adjustments made to create the model. RTK also requires generally a dual frequency GPS module on the drone, which can increase payload weight. A base station must also be set up nearby in order for the drone to receive an RTK correction. While some instruments are equipped with an on-board RTK GPS (e.g. the Phantom 4 RTK, from €5,700), most are not. However, it is possible to georeference the imagery in the post-processing stage using referenced survey targets placed on the ground before data capture. In this case, the survey targets must be captured in the drone imagery and surveyed on the ground using an RTK GPS system (such as the Trimble R10, from €22,000). The surveyed points are known as 'ground control points'. A major advantage of using ground control points, or a combination of RTK and GCPs, is that they can be used to estimate the absolute geolocation error of the model. This can be done by using some of the GCPs to reference the model and using the remaining ones to check how well it is referenced (a form of model validation). Generally, ground control points are the easiest and most cost-effective way to achieve higher accuracy because they do not require additional equipment on the drone.

An alternative to RTK is post-processed kinematic (PPK) geolocation. This method involves correcting the trajectory afterwards using a precisely located local base station. PPK requires same equipment as in RTK, but there is no live transmission between the drone and the base station. This method can achieve similar accuracy results as RTK, but the data must be post-processed. The advantage, though, is that a live signal between drone and base station is not required, so if the signal between the drone and base station is lost for a brief moment, the mission does not have to start again.

It is also important prior to purchasing any equipment to consider local restrictions on maximum flight height and distance from the pilot (see also section 2.4), because this can limit the type of drone that can be used for a project. It would not be wise, for example, to use a fixed-wing drone in an area where the flight height restrictions are 50 m, because a fixed-wing cannot fly slow enough to map effectively at this height. Additionally, some areas have privacy laws prohibiting the collection of high-resolution imagery above private residences.

To summarise, some of the key considerations when comparing drone equipment include:

- Flight time
- Payload capacity
- Ease of use
- Petrol powered versus battery powered
- Cost
- Include/exclude accessories, such as gimbal and camera or sensor
- GPS/GNSS capabilities
- Local restrictions and laws on flight height, distance from operator, and drone weight limits
- Physical environment in which the drone will be flown
- Maintenance requirements

2.2 Sensors

The most common type of sensor used in drone data capture is the RGB[6] camera, used to collect still and video imagery. Other sensors, though, may be used to capture information invisible to the naked eye, such as temperature or vegetation health (Wich and Koh, 2018). These sensors measure radiation in different parts of the electromagnetic spectrum, apart from or in addition to the visible portion. Such sensors are commonly found on satellite platforms used for Earth Observation. The spatial and temporal resolution of satellite data, as well as the presence of cloud cover, though, can limit their applicability.

Five types of sensors[7] used in drone surveying include:

- RGB Cameras
- Thermal Infrared Sensors
- Multispectral Sensors
- Hyperspectral Sensors
- LiDAR Sensors

RGB cameras measure the reflectance of light in the visible portion of the electromagnetic spectrum (wavelengths between 0.4 and 0.75 µm). The resulting image is called a 'true colour image' and is made up of a grid of pixels, each of which contains information about the reflectance or colour of the element in the image. The camera characteristics, along with flight altitude, will dictate the spatial resolution of the resulting images. This is often referred to as the ground sampling distance, or GSD. GSD is a function of the flight altitude and the camera's focal length, sensor resolution, and sensor size (Wich *et al.*, 2018). Table 1 compares the GSD for two camera models flown at an altitude of 100m above ground level (AGL). Spatial resolution limits the detection of smaller objects on the ground, so this is an important consideration for drone survey work. The higher the altitude of the drone, the lower the spatial resolution. For video recording, video quality is limited by the image resolution and the number of frames that can be recorded per second (FPS).

Thermal infrared sensors record temperature data, or the thermal radiation (or heat) emanating from a surface or object. These operate in the long wave infrared portion of the electromagnetic spectrum (8–14 µm). Since our eyes cannot see radiation emitted at these wavelengths, the resulting images are given colours that we can

[6] RGB refers to the bands of the electromagnetic spectrum captured by a typical camera (see in appendix I)
[7] While this is not an exhaustive list, these sensors are commonly used for coastal applications, and so are highlighted in this report.

see – these are called 'false colour images'. Most thermal cameras capture relative temperature data, but more expensive radiometric thermal cameras can capture absolute temperature data, provided the sensor is calibrated to do so. Manufactures of thermal cameras for drones include FLIR, Optris, and Xenics. It is important to note that images captured by thermal sensors generally have a much lower number of pixels than RGB cameras, thus the GSD is also lower (Wich *et al.*, 2018). Thermal sensors may be useful in coastal settings for detection of people (search and rescue), animals (conservation studies), and fires.

In order to understand the capabilities of multispectral and hyperspectral sensors, a basic understanding of the principles of remote sensing is required[8]. Different surfaces reflect different amounts of radiation in different parts of the electromagnetic spectrum. Our eyes can only see light reflected in the visible portion of the spectrum, the portion recorded by RGB cameras. RGB cameras record reflectance in three distinct wavelength bands of the spectrum - red (0.64 - 0.67µm), green (0.53 - 0.59µm), and blue (0.45 - 0.51µm). Multispectral sensors can record reflectance in these and/or other wavelength bands, such as the near infrared (0.75 – 2.5µm). These sensors typically record reflectance in 3-5 bands of the spectrum, which may include portions of the visible spectrum, such as coastal blue band (0.433-0.453 µm), which is especially useful for coastal inspections (USGS, 2020). Sensors with bands in the red and near infrared part of the spectrum are typically used to map vegetation health. Reflectance measured in these parts of the spectrum can be used to calculate the Normalized Difference Vegetation Index (NDVI) for each pixel, which is an indicator of vegetation health. Other features that may be of interest may have different reflectance characteristics in other parts of the electromagnetic spectrum. Sometimes, these can only be mapped using hyperspectral sensors, sensors with many more, but narrower, bands (*i.e.* they have a higher 'spectral resolution'). Since different objects or surfaces of interest have different 'spectral signatures', or unique reflectance characteristics, the choice of which sensor is appropriate depends on the application and may require specialist skills to identify the right sensor and to correctly process the data. A special reflectance target is always required on the ground for calibration of such sensors, as well as a "sunshine sensor" to precisely measure the radiation from the sun at any given moment.

There are two ways to map elevation and structural data using drones. One is to use passive measurement techniques, such as photogrammetry (see section 2.3). This is an indirect way of mapping elevation, in that elevation is derived from the processing of the visible imagery. Light Detection and Ranging (LiDAR) sensors are only recently beginning to be flown on drone platforms. LiDAR sensors provide direct elevation measurements. They work differently from the sensors discussed previously in that they are 'active' sensors, meaning that rather than measuring radiation that is reflected or emitted by an object, they emit their own radiation. They then measure the time it takes for the signal to be reflected back to the sensor, allowing the distance between the sensor and the ground to be calculated. There are two types of LiDAR which can be fitted on a drone: green and red (near infrared). While red LiDAR is much more common on drones (see, for example, VUX-UAV or MiniVUX-UAV1 by Riegl), green LiDAR may be more useful for costal applications, because can penetrate water (up to a certain depth). It also reflects more strongly off vegetation, and therefore may be more useful for vegetation mapping. Green LiDAR systems, however, are much more expensive (see, for example, BathyCopter or VQ-800-G by Riegl). LiDAR sensors must be flown on drones equipped with a highly precise GPS and inertial measurement unit (IMU) to obtain accurate measurements (on the order of mm). The ability of drones to be equipped with LiDAR is relatively new, and these systems can be prohibitively expensive (€100,000+). However, where high precision and accuracy is important, LiDAR is preferred over photogrammetry for elevation and structural modelling.

Figure 4 illustrates raw and processed imagery from various different types of sensors.

	Canon S110	Sony A6000
Focal length (mm)	5.2	20
Number of pixels (sensor resolution)	4000 x 3000	6000 x 4000
Sensor size (mm)	7.6 x 5.7	23.5 x 15.6
Ground sample distance (cm)	3.65	1.95

Table 1: Characteristics of and ground sample distance for two camera models flown at 100m AGL. [Source: Wich *et al.*, 2018]

[8] For a good primer on remote sensing, see, for example, Campbell and Wynne (2011)

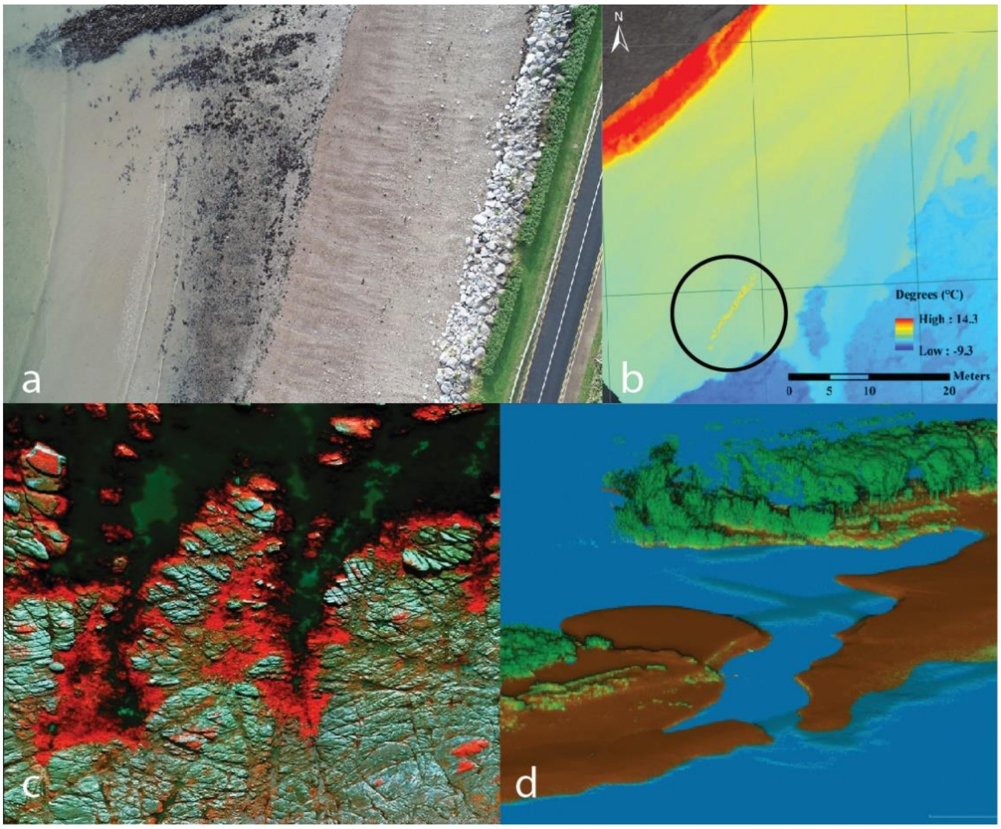

Figure 4: Imagery from different types of sensors. (a) true colour RGB image captured by an RGB camera on a Phantom 4 Pro drone [Source: Sarah Kandrot]; (b) false colour thermal image showing a flock of arctic birds (circled) in Northern Greenland captured by a thermal infrared sensor [Source: Lee *et al.* (2019)]; (c) false colour image illustrating kelp (red) captured by a multispectral sensor. The reds represent areas where there is a high reflectance in the NIR band, typically vegetation. [Source: Science Learning Hub – Pokapū Akoranga Pūtaiao (2020); (d) classified LiDAR data in a coastal setting (green=vegetation, brown=land, blue=water) [Source: Assenbaum (2018)]

2.3 Data collection and analysis software

The tools required for drone data collection and analysis include data capture apps and software for viewing and processing imagery/data.

Data capture apps are used to control the sensor aboard the drone and to set up automated flights. Some apps are built for specific platforms, such as the DJI Go4 App for the Phantom 4 Pro, which allows users to control the camera settings such as shutter speed, aperture, ISO (brightness), etc. and to take photos and videos. They also record flight data, such as time, position, and altitude. Other apps have been designed for specific applications; such the DroneDeploy and Pix4D capture apps, which are designed for photogrammetry applications. Others give more flexibility in relation to automated flight planning, such as the Mission Planner app. Some key considerations for selecting the right data capture app include:

- Compatibility with the drone platform and mobile device being used for data capture
- Features (e.g. what sensor/camera settings does it control; does it offer flight planning)
- Cost (many are free, but advanced features may be paid-only)
- What format can the files be saved as (.jpg, RAW, GeoTIFF[9], etc.)
- Ease of use
- Availability of support

[9] A georeferenced image that can be read by GIS software

For some applications, such as building inspections, visual interpretation of raw imagery or video footage may be sufficient for analysis of the data captured by the drone. For others, such as mapping and 3D modelling (*e.g.* applications discussed in section 3 of this report), software is essential for data processing. Some categories of software for processing drone data include:

- Geographical Information System (GIS) packages (*e.g.* ESRI ArcGIS Desktop or Pro, QGIS, MapInfo)
- Remote sensing packages (*e.g.* ENVI, ESRI ArcGIS Pro, GlobalMapper)
- Photgrammetry/SfM packages (*e.g.* Pix4D, Agisoft Metashape, previously known as Agisoft PhotoScan, DroneDeploy, Meshroom, MicMac[10])
- CAD packages (*e.g.* Autodesk)
- Professional photo editing software (*e.g.* Adobe Photoshop)
- Professional video editing software (*e.g.* Final Cut Pro, Da Vinci Resolve)

GIS packages can be used to georeference imagery, create orthophotos (geometrically corrected 2D maps), generate digital elevation models (DEMs) or 3D textured meshes, and produce other different types of maps from the imagery. They can also be used to detect changes between images of the same area taken at different times (called change detection). Analysis of drone data using GIS may require some degree of expert knowledge, although many local authorities have GIS officers that may be able to carry out such tasks. There have been many recent developments in the field of automatic change detection and image processing with machine learning techniques, such as convolutional neural networks (CNNs) (Quinn *et al.*, 2018; Gray *et al.*, 2019). Although such analyses currently require expert knowledge, there are consulting companies that offer these services, especially for satellite imagery but also for drone imagery (e.g. Svarmi).

There is some overlap between the capabilities of GIS software and remote sensing software. However, for advanced image classification, for example analysis of imagery from multispectral or hyperspectral sensors, remote sensing software, or GIS software with advanced image analysis capabilities, such as ArcGIS Pro, is required. Remote sensing software packages are used for spectral analysis and image classification. Spectral analysis refers to the analysis of multispectral (or hyperspectral) data. For example, maps of the Normalized Difference Vegetation Index (NDVI), a proxy for vegetation health, can be created where reflectance information is available from the red and NIR parts of the electromagnetic spectrum. The software calculates the NDVI using the following equation for each pixel:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where:
NDVI = normalised difference vegetation index (unitless)
NIR = reflectance in the NIR portion of the spectrum
RED = reflectance in the red portion of the spectrum

The resulting image contains pixel values ranging from -1 to +1. A false colour image can be produced by assigning colours to the pixel values to highlight unhealthy versus healthy vegetation. This type of analysis and resulting interpretation requires specialist knowledge. It can, however, be very useful for conservation, habitat mapping, and ecological monitoring. Remote sensing software is also useful for image classification, or the categorisation of pixels based on their reflectance in different parts of the electromagnetic spectrum into different land cover classes. The resulting image, when georeferenced and orthorectified, is essentially a map illustrating the spatial distribution of different features of interest. As highlighted in section 2.2, different objects or surfaces reflect different amounts of light in different parts of the electromagnetic spectrum, thus have unique 'spectral signatures'. While the sensor measures this reflectance, the data must be processed in order to identify or map the features of interest. There are different types of image classification techniques that can be performed using remote sensing software to differentiate between the different classes of features in an image. Effective analysis of multispectral or hyperspectral imagery using remote sensing software requires specialist knowledge, which can be outsourced. Many consultancies and research institutions offer such services.

[10] While Meshroom and MicMac are open source, the other packages mentioned are subscription based.

Another class of software package is used to produce orthorectified 2D maps and 3D models from visible imagery. These are photogrammetry or structure from motion (SfM) packages. Again, there is some overlap between the capabilities of GIS and photogrammetry/SfM packages, but since these packages are designed specifically for the purpose of creating 3D maps and models, they tend to be easier to use for this application. The packages are based on the principle of photogrammetry, whereby multiple overlapping photos are used to generate an orthorectified 2D map or 3D model[11]. Again, these activities should be carried out by experienced professionals, which can be contracted by local authorities to perform such analyses. For example, Pix4D (2019) describe an application of their software whereby a local geoinformatics consultancy was contracted by local authorities to map clifftop hazards and coastal erosion on the northwest coast of France. While photogrammetry can be useful for many applications, it is limited in some cases. For example, homogenous surfaces, such as snow, sand, and tarmac, cannot be accurately mapped using this technique. Wide, sandy beaches with few defining features can therefore be difficult to map using photogrammetry. In addition, there can be multiple sources of errors or noise in photogrammetry, which means data processing can be onerous.

Computer aided design (CAD) software packages are used by architects and engineers (amongst others) to create technical drawings of built structures. Drone data usually need to be processed using other software, such as Pix4D Survey or Virtual Surveyor, before they can be imported into CAD software. The use of different software packages allows drone imagery to be overlaid on to technical drawings (or used to create technical drawings) of buildings. This can be useful, for example, for planning building maintenance work.

Finally, professional photo and video editing software can be used for tourism, education and outreach, and cultural heritage applications. Packages such as Adobe Photoshop can help to enhance drone images by allowing users to adjust the brightness, contrast, and other settings. Video editing software can be used to create professional videos from drone footage. Depending on the application, professional expertise may be required.

2.4 Limitations and logistical challenges

Operating a drone and analysing the data requires certain skills, knowledge of best practice, and an understanding of the limitations of platforms, sensors and data (Alliance for Coastal Technologies, 2018).

Some important practical considerations for drone use include:

- Local regulatory framework in relation to the use of drones
- Privacy and data protection issues
- Flight traffic in the area (the possibility of a plane or helicopter entering the area the drone is being operated in)
- Drone capabilities
    - Flight time
    - Resolution
    - Coverage
    - Accuracy
- Field survey limitations
    - Weather
    - Minimising environmental impacts (e.g. impacts on wildlife, such as birds)
    - Terrain
- Costs (equipment, software, insurance, training, etc.)
- Frequency of drone usage (e.g. if a project only requires data collection once, or maybe once a year, it may be more cost-effective to out-source this work to a company or contractor that already has the equipment and knowledge to obtain the data quickly and effectively. There is a huge start-up cost to establishing a drone department, with a lot of trial and error involved, which can be costly to companies and projects. Outsourcing drone data collection can be cheaper and more effective in many cases.)
- Data storage

[11] See Aber *et al.* (2019) for a primer on photogrammetry from UAS imagery.

- Alternatives to drone data
- Failures/setbacks of any sort (e.g. drone crash, sensor failure, fly away or similar)

Perhaps the most important factor when considering the use of drone technology is the regulatory framework in relation to the safe use of drones. This can potentially limit some applications. For example, most countries require that drones be flown within the operator's visual line of sight (VLOS). In other words, the drone must be visible in the sky at all times. If a very large survey is to be undertaken, this could mean taking off and landing at multiple locations, limiting the efficiency of the technology. Some countries do give out special exemptions to fly beyond visible line of sight (BVLOS), but it can be very difficult to obtain such permission. Some common criteria that may covered by legislation includes:

- Flying Distance Restrictions (*e.g.* maximum altitude / distance from take-off)
- Weight Classification (*e.g.* different rules for different size drones)
- Over Crowed Areas Restrictions
- Flight Permissions
- Areas' Distance Restrictions (*e.g.* restrictions in different classes of airspace)
- Drone Registration
- Buildings' Distance Restrictions
- Safety Insurance
- Piloting Certificate
- Purpose of Flights
- Operators' Age Limitations
- Operation Plan
- Air Flight Zones
- Weather Conditions
- Wildlife/birds

(Tsiamis *et al.*, 2019)

There is considerable diversity in drone legislation between countries (Tsiamis *et al.*, 2019), although national rules in the European Union are to be replaced by a common EU legislation in 2020 to facilitate cross-border operations[12]. It is important for drone operators to familiarise themselves with these rules and ensure they are compliant to avoid fines, injuries or damage to property. A recent study involving 350 local authorities in the UK indicated that despite the increasing adoption of drone technology by local councils, many do not have appropriate policies in place to ensure that they are compliant with drone regulations (Gee, 2019). Such policies can help to limit safety and/or legal issues. More information on European legislation will be included in a later COAST project report. Links to information about drone use from the aviation authorities in the COAST Project Partner regions are provided in appendix II.

Legislation in relation to drones is not limited to safety, but also includes regulations in relation to privacy and data protection. For example, in the EU, non-recreational drone operations must comply with the Data Protection Directive on the protection of individuals with regard to the processing of personal data and on the free movement of such data. Personal data that can inadvertently be captured by drones include facial images or car registration plates. Drone operators have certain obligations to ensure such data are handled appropriately and in line with national and international laws. Such regulations and compliance measures are usually covered in detail by pilot training programmes. It is strongly recommended that any local authority considering utilising drones as part of their activities ensure that staff are suitably trained to do so and that they have a policy or strategy in place that deals specifically with the use of drones and the data they capture (e.g. see Gee, 2019).

The capabilities of the drone platform and sensor are also limiting factors. For example, battery energy limits flight time, meaning the drone may need to take off and land multiple times to change the batteries - or, worse,

[12] See Easy Access Rules for Unmanned Aircraft Systems (Regulation (EU) 2019/947 and Regulation (EU) 2019/945)

the drone could run out of battery in the sky. This may seem unlikely, but it can happen where strong winds force a returning drone to use more battery power than anticipated. Professional drone pilots avoid such scenarios through careful flight planning.

The spatial resolution of the captured imagery can also be a limiting factor. For example, if the drone is flown at height and the GSD is low, certain objects of interest may not be visible in the resulting imagery. For multispectral and hyperspectral cameras, the spectral (number and width of bands in the electromagnetic spectrum) and radiometric resolution (capacity of the instrument to distinguish differences in light intensity or reflectance) will also limit object detection. Finally, for mapping applications, the quality of the mapped data (in terms of accuracy and precision) will be influenced by factors including (but not limited to):

- the positional accuracy of the GPS
- the number of ground control points
- the location of the ground control points
- the sensor characteristics
- the type of terrain
- visibility
- brightness
- overlap of images
- angle of the camera
- vegetation
- presence of manmade objects

These are all important considerations for beach survey applications.

Drone surveys can be limited by the geographical characteristics of the site and the survey conditions on the day. For example, field surveys over vertiginous terrain, such as cliffs or mountains, must be planned carefully to avoid crashing into the ground, losing visual line of sight or connection with the drone, and/or capturing images of variable resolution. Surveys over water must also be planned carefully, especially where accurate georeferencing necessitates the use of ground control points. Surveys in environmentally sensitive areas may require consideration of how to minimise or avoid potential negative impacts on wildlife, such as birds, which are known to attack drones. Finally, it is important to understand the limitations of your drone in certain weather conditions, as some models cannot be controlled in strong, or even moderate and gusty, winds or rain.

Another important consideration for local authorities who wish to use drone technology is costs. While consumer grade drones have come down in price, the cost of other required equipment and software can be prohibitive. For example, table 2 shows the start-up budget for the United States Geological Survey's Aerial Imaging and Mapping (AIM) Group, which totalled $160,000 (Alliance for Coastal Technologies, 2018). This does not include insurance, flight training, software training, or pilot certification fees. There is also a considerable amount of time required to invest in a new drone department, as well as additional costs associated with staffing and investigating and managing the purchasing of equipment. Given the costs and expertise required for certain applications, local authorities may choose to sub-contract drone work.

Finally, it is important to determine if a drone is the right tool for the job. Some questions worthy of consideration include:

- Can the required data or information be obtained on the ground or using data collected by an alternative aerial or satellite platform?
- What extra added value is the drone data providing that would be impossible to achieve with ground-based data or satellite data?
- Can we avoid putting people at risk by using drones instead of employing more dangerous traditional survey methods, such as field surveying in hazardous environments or using manned aircrafts?
- Do you have the necessary equipment and skills (or access to both) to undertake the work, including the manpower/resources to extract information from the data that you need?
- Do you have access to expert knowledge that can interpret the data? Can you provide necessary training to use the data to its full potential, or would it be better to outsource it to an expert?

If these questions are not answered up front, then drone data can add extra work and frustration to a project where project members are already overwhelmed. Where drone work is deemed the only cost-effective means of achieving an objective, it should be noted that this should never replace fieldwork, but complement it, as ground verification is essential for accurate interpretation of the data.

Item	Cost	Quantity	Subtotal
UAS Platforms			
• 3DR Solo (quadcopter)	$1,200	3	$3,600
• Bird's Eye View FireFLY6 Pro (fixed wing)	$15,000	1	$15,000
Cameras			
• Gopro4 (video)	$400	1	$400
• Ricoh GRII (high resolution, global shutter)	$600	3	$1,800
• MicaSense RedEdge (multispectral)	$5,000	1	$5,000
GPS Systems			
• Spectra Precision SP80 GNSS receivers	$20,000	4	$80,000
Processing			
• Agisoft Photoscan licenses	$3,500	4	$14,000
• High-powered processing computers	$10,000	3	$30,000
• Synology disk station raid storage	$10,000	1	$10,000
		Total	**$160,000**

Table 2: Start-up budget for the United States Geological Survey's Aerial Imaging an Mapping (AIM) Group [Source: Alliance for Coastal Technologies (2018)]

3. Applications for sustainable development of coastal systems

In recent years, satellite-based EO products have become more accessible and more widely used to address coastal and marine management issues, with opportunities to support the SDGs highlighted by Politi *et al.* (2019). However, such opportunities offered by drone platforms are yet to be fully explored or exploited. In this report, we identify nine areas in which drone technologies can support ICZM and the UN SDGs at the coast. We discuss specific applications from around the world, which may be of interest in particular to local authorities, for each of these areas. We identified 16 targets across 10 (out of the 17) SDGs to which drones can contribute data and information. For each section, we present examples of applications, discuss some of the technical and methodological challenges faced by users of the technology, and conclude with a summary table outlining the relevance of drone technology to the UN SDGs.

3.1 Habitat mapping, and biological and natural resource assessment and management

The use of drones for habitat mapping and biological and natural resource assessments are among the most common applications of drone technologies in the coastal zone. Information from such surveys is widely being used for sustainable management and conservation purposes. Drones can help to map key habitats and to monitor ecological populations, behaviour, and health. They can also be used to manage human interactions with marine species and to monitor other anthropogenic activities that can have negative environmental impacts. This information is important for protecting threatened marine life and for supporting Blue Growth, by providing policymakers, planners, and managers with an evidence-base for decision-making.

Mapping and identifying the geographic distribution of different habitats is a primary use of drones in the coastal environment. Blue Carbon ecosystems are a key habitat due to their potential to sequester large amounts of carbon. Quantification of these carbon stores has become a priority of many nations in response to the climate crisis, yet the global coverage of many sizable carbon stores, such as seagrass, remains largely unknown (WEB, 2014; Röhr *et al.*, 2018). Drones have been successfully used to map seagrass habitats, using multispectral, hyperspectral and RGB data (Duffy *et al.*, 2018; Jeon *et al.*, 2020). For example, Duffy *et al.* (2018) used a 3D Robotics Solo multi-rotor drone with a 3D printed-sensor mount to collect hyperspectral imagery of *Zostera noltei* in Pembrokeshire, Wales (Figure 5). They explored how such cameras can be used, the accuracy of different image classification techniques, and the effectiveness of their methods at identifying other species and habitats. This team interestingly noted a high accuracy associated with interspecies classification in heterogeneous meadows, which provides opportunities to advance beyond a boundary delineation of such habitats and identify within-patch variation of meadows. Drones have also been used to monitor other key Blue Carbon habitats, including mangrove forests in Malaysia (Ruwaimana *et al.*, 2018), China (Wang *et al.*, 2020), and Australia (Warfield and Leon, 2019) and saltmarshes in Scotland (Green *et al.*, 2020), USA (Doughty and Cavanaugh, 2019), and China (Dai *et al.*, 2020), among many other countries. By identifying the overall distribution of these habitats, estimates of the monetary value of CO_2 can be calculated, with Green *et al.* (2018) estimating the value of *Zostera marina* in the UK of between £2.6 and 5.3 million.

Drones have also been used to identify nursery habitats for many rare and/or commercially important fish species. For example, Ventura *et al.* (2016) attached a GoPro to a quadcopter and used this imagery to undertake supervised classification of the RGB image bands, resulting in the creation of a fine-scale map of fish nurseries around Giglio Island in Italy. Such approaches to modelling fine-scale habitats of nurseries have been extended to identify the most suitable sites to undertake underwater censuses, which reduces the amount of time and resources for more targeted underwater surveys (Ventura *et al.*, 2017). Drones have also been used to map coral reefs. In the Pacific, NASA and the University of Guam used drones to create a centimetre resolution digital model of coral reef structure, with the aim to undertake repeat surveys to monitor how the habitat is changing over time (Silver, 2019). Quantifying change is a key feature of many of these implementations, with the ease and speed of mapping allowing for the potential monitoring of these habitats over time as drones become more ubiquitous.

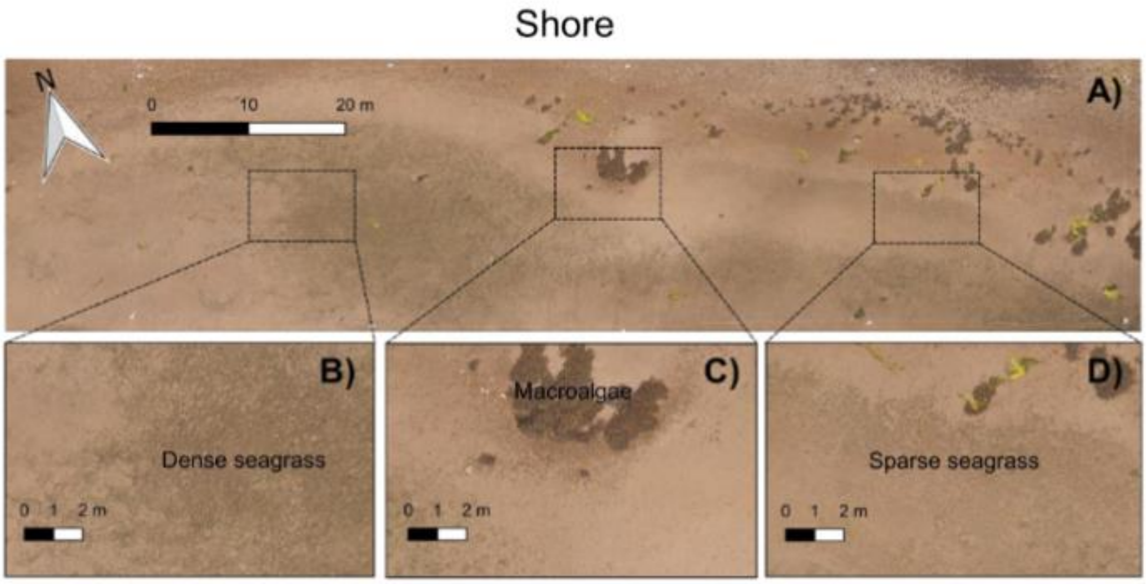

Figure 5: RGB drone imagery of an intertidal seagrass habitat in the UK, which can be used to help quantify the Blue Carbon store. [Source: Duffy *et al.* (2018)]

Drones are increasingly being used to limit interactions between people and animals in coastal areas. For example, Butcher *et al*. (2020) explored how drones can be used to manage conflict between swimmers and sharks. Using a multirotor drone (DJI Inspire), they assessed the potential to detect shark analogues in the water across a range of environmental conditions in Australia. Such a method provides an opportunity for real-time detection and alerts for the protection of bathers, although this research found that detectability decreased with higher winds and poorer water visibility.

Drones have also been used for surveillance of illegal fishing activities, which can support more sustainable management of fish stocks. In Belize, quadcopters with live video streams have been deployed to increase the patrolling of the coastline to detect and enable real-time enforcement of illegal fishing (Howard, 2016). Moreover, the collection of video footage also enables successful prosecution. Toonen and Bush (2020) note that this has also been adopted in other coastal regions, including Jamaica and Costa Rica. The ability of larger drones to traverse up to 500km over a 2-day period (Toonen *et al.*, 2020) enables drones to be highly effective in the management of this natural resource and is strongly tied to the enforcement and compliance of environmental law, which is further explored in section 3.3 of this report.

Finally, drones have been widely used to manage agriculture in terrestrial ecosystems, optimizing agriculture operations, monitoring growth, and identifying the environmental impact of events such as flooding (Puri *et al.*, 2017). In Ghana, UAVs have been used to monitor the impact of flooding within the Volta Delta, quantifying the amount of land (including farms) that have been lost to flooding and erosion (Addo *et al.*, 2018). Such information is key to the successful management of coastal communities to inform resilient planning opportunities, as well as to inform the provision of compensation to land managers. Further applications related to disaster assessment and management are discussed in section 3.7 of this report. Table 3 outlines the SDG goals, targets and indicators to which drones can contribute data and information for habitat mapping and biological and natural resource assessment and management at the coast.

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 14 Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.	Target 14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans	None	Drone technologies can be used to document and map the distribution of marine and coastal resources (*e.g.* fisheries, seagrass meadows), providing policymakers, planners and managers with the evidence-base required for effective decision-making and management
GOAL 15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	TARGET 15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	INDICATOR 15.5.1 Red List Index	Drone technology can be used to document and map coastal biological resources (*e.g.* saltmarshes, mangrove forests) and to monitor changes in the distribution of threatened species

Table 3: SDG goals, targets and indicators to which drones can contribute data and information for habitat mapping and biological and natural resource assessment and management at the coast.

3.2 Ecological monitoring

Ecological monitoring is the system of regular observation of species and habitats in both space and time. UAVs have been regularly used to undertake bird censuses in both natural environments and urban environments to identify how populations are changing. In county Dublin, Ireland, Roughan & O'Donovan (2018) used aerial imagery obtained from two drones (Yuneec H520 and the DJI Phantom 4 Pro+) to identify buildings on which herring gulls were nesting. They identified 451 nests in total and noted that birds favoured flat roofs or built their nests against chimney stacks. This work was commissioned in part to address the increasing conflict between humans and gulls in the region, but such drone surveys are beginning to replace ground surveys of nesting sites for many remote coastal environments (e.g. Rush *et al.*, 2018). Research has noted higher accuracy when using drones to conduct bird censuses compared with ground surveys in natural and often remote environments (*e.g.* cliff-tops). This is in part due to the increased ability of drones to identify camouflaged chicks. However, counts from drone surveys may be skewed where birds flee their nests in response to an approaching drone, exposing chicks to ground predators, thereby increasing predation rates (Brisson-Curadeau *et al.*, 2017). Measures can be taken to avoid such disturbance, though, such as keeping a safe distance from nesting birds (Brisson-Curadeau *et al.*, 2017).

Drones have also been successfully used to undertake aerial surveys of marine mammals. In Australia, Hodgson *et al.* (2013) undertook the first Australian UAV survey trial of dugongs. Using a ScanEagle UAV and digital SLR camera, they flew a 1.3km^2 area capturing over 6000 images and over 600 recordings of dugongs, with turbidity the only factor that negatively impacted detection rate. Similarly, Ocean Research and Conservation Ireland (O.R.C. Ireland) initiated the FlukeFollow project in 2018, which uses UAVs to monitor whales and dolphins in Irish waters (Ocean Research & Conservation Ireland, 2020). Drones have been widely used to collect count and density data on marine mammals (Hensel *et al.*, 2018; Colefax *et al.*, 2019; Palomino Gonzalez, 2019), with many Environmental Impact Assessments now requiring aerial surveys as part of their remit, and conservation management plans requiring stock assessment to support funding allocations. Such surveys are highly regarded due to their higher accuracy in counts; however, little is known regarding impacts on the behaviour of mammals in response to UAVs (Smith *et al.*, 2016).

Monitoring the behaviour of marine taxa is becoming a prominent avenue for drone research, particularly due to the coupling of this technology with biologging techniques (Schofield *et al.*, 2019). Drone footage can be monitored to quantify interactions between individuals. For example, Schofield *et al.* (2017) investigated whether departure of male sea turtles from breeding sites was driven by changes in the receptiveness of females or the probability of successful mating attempts, quantifying this through the sex ratio of all individuals within the footage. Drones have also been used to monitor the health of species. For example, in Australia, drones were coupled with specialised equipment to capture the blow samples of 19 Eastern-Australian humpback whales in order to test for novel viruses (Geoghegan *et al.*, 2018). They characterised the virome of the blow (or exhaled breath) and found six novel virus species. Such approaches are increasingly being used in Australia (see also Pirotta *et al.*, 2017) and demonstrate the potential for such equipment to monitor the disease ecology of marine mammals (Figure 6).

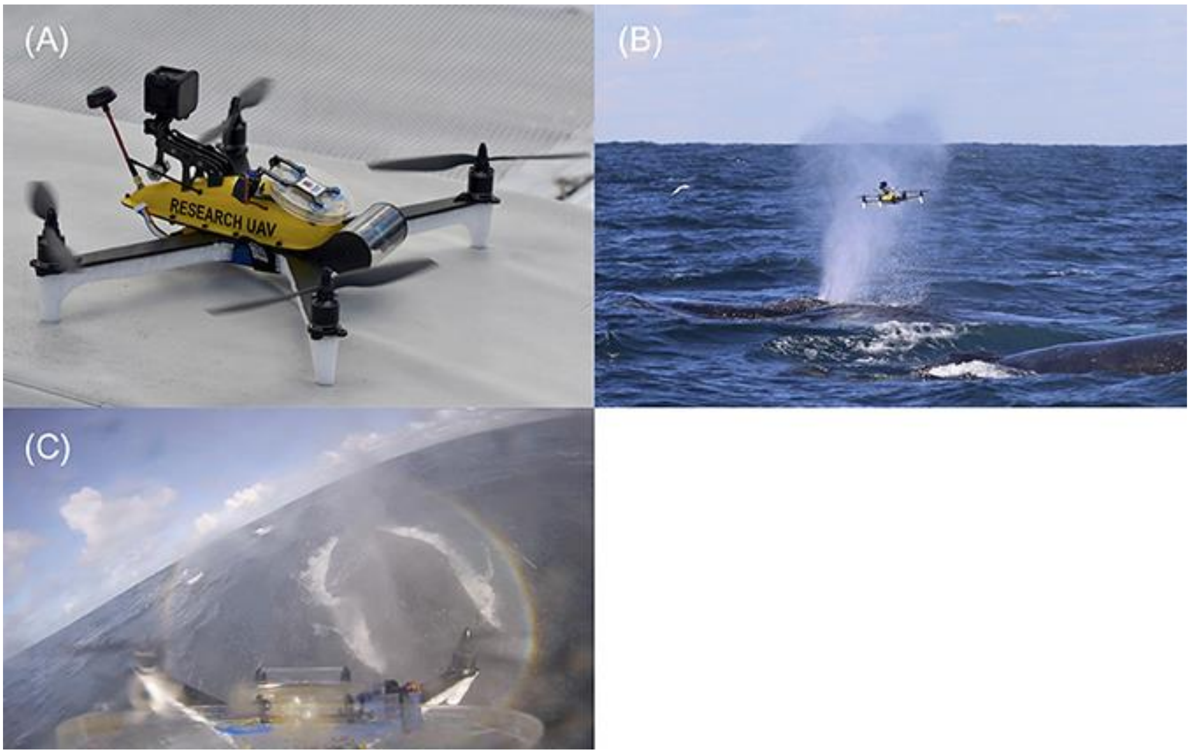

Figure 6: (A) Purpose-built UAV designed to sample whale blow. **(B)** UAV sampling whale blow. **(C)** Screenshot from the UAVs on-board GoPro camera mid whale sample collection. [Source: Pirotta et al. (2017)]

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	TARGET 15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	INDICATOR 15.5.1 Red List Index	Drone technology can be used to monitor the abundance, behaviour, and health of marine species, providing an evidence-base for more effective management activities

Table 4: SDG goals, targets and indicators to which drones can contribute data and information for ecological monitoring in the coastal zone.

3.3 Environmental law enforcement and compliance

There are several examples of the use of drone technology for environmental law enforcement and compliance. In Ireland, eighteen councils are using drones to visit known fly-tipping sites (*The view from above: drones and public services*, 2020). Waterford City and County Council are using footage from a DJI Phantom quadcopter in their investigations into fly-tipping and illegal dumping, which have led to several notices of fines being executed (Parker, 2018). In the Philippines, Ezequiel *et al.* (2014) describe how drone footage has been used to identify unregistered fishpens in one of the world's most threatened lakes. This was the result of a collaboration between members from industry, local government, and academia with the aim of promoting the acquisition, post processing, analysis and sharing of drone-based aerial imagery. They used GIS and remote sensing techniques to overlay licenced pens on the drone imagery so that unlicensed pens could be easily identified (Figure 7). This information is important to help ensure the carrying capacity limit of the lake is not exceeded. Jiménez López and Mulero-Pázmány (2019) and Beaubien (2015) document how a conservation group is using fixed-wing drones to detect illegal mining and logging in the Peruvian Amazon. The private Los Amigos conservation area covers 145,000 hectares, and there are only a limited number of rangers on the ground. With their long range and ability to remain in the sky for long periods, the fixed-wing technology allows the group to more quickly identify and investigate illegal activity. Nuwer (2017) describes how another conservation group is using thermal cameras, also mounted on fixed wing drones, to combat poaching in Malawi's Liwonde National Park. This allows them to detect illegal activity on the ground, even at night. In Ireland, the Irish Naval Service used a drone to survey the extent of an accidental oil spill in Bantry Bay (O'Shea, 2020). The footage can be used as part of an investigation into the incident. In the US, drones are also being used at sea to support the enforcement of no-discharge zones, for example where the release of bilge water is restricted (Alliance for Coastal Technologies, 2018).

These applications demonstrate how drones can provide data and information that can contribute to more effective ICZM practices. While some of the applications described above were not necessarily coastal, they are still relevant as they may be applied in coastal settings. For example, drones can be used to identify unlicensed coastal aquaculture sites. This can help to ensure aquaculture practices are sustainable. The potential applications of drones for environmental law enforcement and compliance in coastal environs directly address the UN SDGs outlined in table 5.

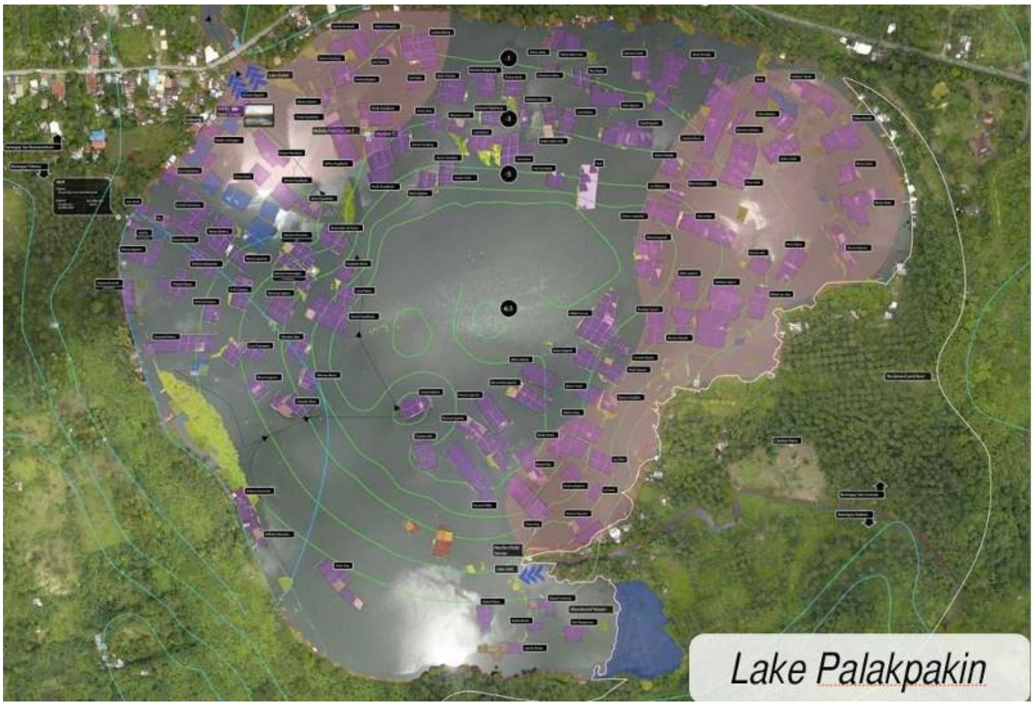

Figure 7: Orthomosaic, produced from drone imagery, of Lake Palakpakin, Philippines with annotated information on fishpens. Unlicensed pens can be identified by overlaying the known locations of licensed pens on the imagery using GIS software. [Source: Ezequiel *et al.* (2014)]

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 6 Ensure availability and sustainable management of water and sanitation for all	TARGET 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	INDICATOR 6.6.1 Change in the extent of water-related ecosystems over time	Drones can help to identify and reduce illegal dumping and aquaculture activities, improving the quality of water-related ecosystems
GOAL 14 Conserve and sustainably use the oceans, seas and marine resources for sustainable development	TARGET 14.4 By 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics	INDICATOR 14.4.1 Proportion of fish stocks within biologically sustainable levels	Monitoring illegal aquaculture practices can help to reduce destructive fishing practices
	TARGET 14.6 By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the World Trade Organization fisheries subsidies negotiation [c]	INDICATOR 14.6.1 Degree of implementation of international instruments aiming to combat illegal, unreported and unregulated fishing	Drones can help to improve the degree of implementation of international laws regulating unreported and unregulated fishing activities
GOAL 15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	TARGET 15.7 Take urgent action to end poaching and trafficking of protected species of flora and fauna and address both demand and supply of illegal wildlife products		Drones can help identify poachers and illegal deforestation activities and bring perpetrators to justice

Table 5: SDG goals, targets and indicators to which drones can contribute data and information in the area of environmental law enforcement and compliance at the coast.

3.4 Pollution management

The use of drones to combat coastal and marine pollution has been documented in a number of instances. In Japan, Project Sea Unicorn (IKKAKU) brings together an interdisciplinary team of startups, SMEs, large enterprises, and academic institutions to promote the development and commercialisation of innovative technologies that will reduce ocean debris (Leave a Nest Co. Ltd., 2020). One of the three teams working on the project will focus on the development of a global marine debris monitoring system that uses data from satellites and drones. This data will be used to predict the arrival of debris at the coast to make coastal clean-up operations more efficient. A preliminary evaluation of such an application is described by Watanabe *et al.* (2019). They designed an experiment to test the effectiveness of a real-time object detection algorithm at identifying marine debris in the Ishikari river estuary in Hokkaido. The deep-network model was able to successfully detect plastic bottles, plastic bags, driftwood, and other debris on the ocean surface and on land from visible drone video footage. The authors envisage the technique could be used in combination with satellite observation to assist with clean-up operations. For example, a drone swarm could be activated and sent to a particular area where abnormal trends are detected by satellite imagery to examine the area in more detail. Similar experiments have been conducted in Hawaii and Greece using various types of drone platforms and sensors (Alliance for Coastal Technologies, 2018; Topouzelis *et al.*, 2019) and work is currently underway in Spain to test the technical and commercial potential of such techniques (LITTERDRONE, 2020). Several citizen science projects have also demonstrated how drones can help to address the marine littler problem (Campbell *et al.*, 2019; Fritz *et al.*, 2019; Jiménez López *et al.*, 2019). Projects such as the Marine Litter DRONET encourage citizen scientists to undertake their own marine litter surveys using a standardised methodology (Kohler, 2018). The images are being used to help train an object-detection system to automatically detect debris in drone imagery. So much research effort is being invested in automatic debris detection because manual detection from thousands or hundreds of thousands of drone images is not practical.

Poor water quality due to nutrient pollution and wastewater discharge is another problem in some coastal and marine environments. Nutrient flows from industrial, urban, and agricultural activities can trigger harmful algal blooms (HABs), overgrowths of algae that can produce dangerous toxins. Alliance for Coastal Technologies (2018) describes how labs in Florida and Virginia, USA are exploring the use of drones for early detection and tracking of HABs using hyperspectral sensors, although there are still many challenges to be overcome before this can become practical for coastal management activities (Kislik *et al.*, 2018). Martin *et al.* (2018) have also explored the applications of hyperspectral sensors, this time for monitoring coastal bathing water quality in the Canary Islands. A hyperspectral sensor mounted on a multi-rotor platform was used to obtain indicators of the presence of bacterial pathogens. While the results of the study were promising, the technique is still experimental.

The applications described above directly address SDG goals 6 and 14. The specific targets and indicators to which drones can contribute data and information are summarised in table 6.

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 6 Ensure availability and sustainable management of water and sanitation for all	TARGET 6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	INDICATOR 6.3.1 Proportion of domestic and industrial wastewater flows safely treated INDICATOR 6.3.2 Proportion of bodies of water with good ambient water quality	Multispectral, thermal, and hyperspectral sensors mounted on drone platforms can help to monitor water quality, although there are still many challenges to be overcome before this can become practical for coastal management activities
GOAL 14 Conserve and sustainably use the oceans, seas and marine resources for sustainable development	Target 14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	None	Drones are an effective means of efficiently providing data and information on debris and nutrient pollution, assisting with targeted cleanup operations

Table 6: SDG goals, targets and indicators to which drones can contribute data and information in the area of coastal and marine pollution management.

3.5 Digital heritage documentation, preservation, and conservation

The use of drone technology for digital heritage documentation, preservation, and conservation is well documented, particularly in relation to natural, built, cultural, and archaeological heritage sites. On behalf of English Heritage, a charity that manages hundreds of heritage sites in England, Historic England (2017) used a combination of drone data, photogrammetry, and 3D printing to produce a 3D display model of Tintagel Island and Castle (on the Cornwall coast) for an exhibition at a newly opened visitor's centre (Figure 8). The drone survey, which was undertaken by a professional surveying company, was obtained using a visible camera mounted on fixed wing and multi rotor platforms to increase efficiency while ensuring maximum coverage of the site. Historic England processed the data using photogrammetry to create a 3D digital computer model, and then a reconstruction artist produced a physical 3D scaled printed model of the island and a section of the adjoining mainland. In the visitor centre, an overhead projection system overlays the model with video showing the development of settlement and use of the island, enhanced by an audio soundscape. The project helps to educate the public and celebrate the natural and built heritage of the local area. Similar work was undertaken by Themistocleous *et al.* (2015) at the Byzantine church of Panagia Phorbiotissa in Asinou, Cyprus, a UNESCO World Heritage Site.

In Italy, Brumana *et al.* (2012) describe the use of visible oblique drone imagery to support landscape heritage analysis and planning. They show how drone images can be used to reconstruct panoramic views and simulate the visual impact of planned developments on the landscape, using examples from the Alpine foothills of Lombardy. The resulting imagery can be used to ensure proposed developments are in line with regulatory guidelines for provincial and municipal planning, such as those outlined in the European Landscape Convention. Also in Italy, Candigliota and Immordino (2013) showed how drones can be used to monitor and manage structural and architectural damage to built heritage sites following an earthquake. They used a visible camera mounted on helicopter and quadcopter platforms to survey a number of damaged historical buildings, including a UNESCO world heritage site, following an earthquake in Emilia-Romagna. The damage to the buildings meant that they were inaccessible, but the damage could be safely assessed from the high-resolution drone imagery. This allowed the municipality to more efficiently plan recovery works. Similar work was also undertaken in Italy by Achille *et al.* (2015) and Trizzino *et al.* (2017), although they used photogrammetry techniques to create 3D visualisations of damaged structures.

Many built heritage sites around the world are in poor condition, and this could present a public safety hazard. One such site is the abandoned Ashnott lead mine in North Lincolnshire. Historic England (2017) surveyed the site using a fixed-wing drone to highlight places where the collapse of old, poorly sealed shafts presented a danger to livestock and hill-walkers. The surveys were then used to plan the installation of new fences, intended to safeguard the remains.

Many of the world's coastal heritage sites have been submerged or are under imminent threat of submergence because of changing sea-levels. This can occur either due to changes in the Earth's climate or where tectonic or even anthropogenic activity[13] causes the earth's crust to shift or sink below the sea-surface. In Greece, several submerged ancient harbours have been discovered along the coast of Lesbos Island, in the Aegean Sea (Harff *et al.*, 2016). Papakonstantinou *et al.* (2019) explored how drones can be used to map such sites. They used visible drone imagery and photogrammetry techniques to create detailed 3D models of two sites at Mytilene and Eresos. This enabled the discovery of new hidden structures. Such information can be used for coastal heritage conservation planning and management. Skarlatos and Savvidou (2015) undertook similar work in Cyprus, but highlighted the technical difficulties in creating accurate orthomosaics of submerged sites.

In Russia, Nicu *et al.* (2019) used drone imagery and photogrammetry in an analysis of coastal archaeological heritage sites threatened by flooding and coastal erosion on the shores of the Kuibyshev reservoir. They were able to identify and quantify the number of sites impacted by the creation of the reservoir in 1957. This information can be used by local authorities in future management plans and conservation strategies. Similar work is being undertaken in Ireland and Wales as part of the EU-funded CHERISH (Climate, Heritage and Environments of Reefs, Islands, and Headlands) project (CHERISH, 2020). The project explores the use of digital surveying technologies, including but not limited to drones and photogrammetry, for the protection and

[13] Such as groundwater or oil and gas extraction

management of heritage sites. Its aims include the generation of best practice guidelines for collecting and analysing such data, the identification of "at risk" cultural heritage sites in Ireland and Wales, and the development of mitigation and conservation guidance plans for their future management and protection. While photogrammetry mapping is becoming more commonly employed for coastal heritage applications, drone-based LiDAR is also being used (e.g. Skarlatos *et al.*, 2015; CHERISH, 2020), but this technique is considerably more expensive.

Several others document the use of drone technologies for archaeological heritage investigations and conservation in coastal settings. In Australia, Kurpiel *et al.* (2018) used visible imagery and photogrammetry to record the presence of Aboriginal cultural heritage at a coastal dune site prior to the imminent agricultural development of the landscape. The pending development meant that the physical and topographical context in which artefacts were found could be lost forever. The digital recording will allow archaeologists to continue to investigate the site (to some extent), even after development has occurred. In Canada, researchers at the Hakai Institute are using drone technology to create detailed maps of ancient clam gardens created by First Nations (Alliance for Coastal Technologies, 2018). Many such sites have been destroyed by storms, tectonic activity, or historic logging activities (Holmes, 2016). By digitally recording the remains of the surviving sites, a record of their existence remains.

SDG goal 11 emphasises the protection and safeguarding of the world's natural and cultural heritage sites. The applications outlined above demonstrate how drone technology can help to contribute to this endeavour. Table 7 summarises the specific targets and indicators to which drones can contribute data and information in relation to digital heritage preservation, documentation, and conservation at the coast.

Figure 8: Model of Tintagel Island and Castle, Cornwall, UK, created using drone imagery, photogrammetry, and 3D printing techniques. [Source: Historic England (2017)]

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 11 Make cities and human settlements inclusive, safe, resilient and sustainable	TARGET 11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage	None	Drone technologies can be used to document, digitally preserve, and manage cultural and natural heritage sites
	TARGET 11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	INDICATOR 11.5.2 Direct economic loss in relation to global GDP, damage to critical infrastructure and number of disruptions to basic services, attributed to disasters*	Drone technologies can be used to (safely) help quantify the economic loss of damaged or destroyed cultural heritage sites in the event of a disaster (*e.g.* following an earthquake)

Table 7: SDG goals, targets and indicators to which drones can contribute data and information in the area of digital heritage preservation, documentation, and conservation at the coast. *A metric that contributes to this indicator is 'Direct economic loss to cultural heritage damaged or destroyed attributed to disasters'

3.6 Emergency response

Emergencies at the coast can arise from accidents or natural disasters, such as storms or earthquakes. The latter are dealt with in section 3.7 (Disaster assessment and management) of this report. This section focuses on search and rescue operations.

Drones can be very effective tools in supporting search and rescue activities (Burke *et al.*, 2019; Jiménez López *et al.*, 2019; Rajabifard, 2019). Drone platforms equipped with visible or thermal sensors can be used to search large, potentially difficult-to-access or inaccessible areas and detect people in distress on the ground or at sea. Thermal sensors are particularly suited to such activities because warm objects, such as people or animals, stand out against the relatively cooler background in the false colour images. This makes them easier to detect than from visible imagery or from the view of rescuers aboard an airplane or helicopter (Figure 9). This is critical in time-sensitive situations, where people's lives may be at risk. Thermal cameras have the added advantage of being able to detect objects both in the day or at night[14]. Manual detection of humans from the imagery or video footage, though, can be a difficult task, especially over a large search area. Artificial intelligence (AI) algorithms are now under development to automate the detection of people, both from visible and thermal drone imagery, for search and rescue operations. These, however, are still in the very early stages of development and not yet practical for real-life operations (Lomonaco *et al.*, 2018; Burke *et al.*, 2019). Nevertheless, Lomonaco *et al.* (2018) suggest such AI-equipped platforms could eventually be used to power 'intelligent drone swarms' for search and rescue operations at sea, for example in the context of the migrant crisis in the Mediterranean Sea. Other examples of potential drone uses in search and rescue operations include use of drone imagery to gather information on the ground state, use of drones as communications relay points, and use of drones to deliver life-saving equipment, such as life vests, to people in distress (Bäckman *et al.*, 2018; Seguin *et al.*, 2018; Burke *et al.*, 2019). In 2018, the leading drone manufacturer DJI published a report documenting real-world examples of drone use in search and rescue operations. Between May 2017 to April 2018, they counted at least 65 people who were rescued from peril by use of a drone (DJI Technology Inc., 2018).

The use of drones for search and rescue operations can help to support the SDGs at the coast (Lomonaco *et al.*, 2018). Table 8 outlines the relevance of drone technology in relation to the specific goals, targets, and indicators to which it can contribute data and information.

Figure 9: Thermal imagery used in a SAR operation in Iowa, USA. In this instance, six people who went missing on a river at night were identified and rescued by the Decorah Iowa Fire Department. People are clearly visible (lower right of centre) in the image against the dark background. [Source: DJI Technology Inc. (2018)]

[14] This is especially effective in colder areas where the temperature difference (or the emissivity) of the background is much greater compared to warmer regions. Conversely, in warmer environments, detection can be more challenging.

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 1 End poverty in all its forms everywhere	TARGET 1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	INDICATOR 1.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	Drones can help to reduce the number of deaths, missing persons and directly affected persons attributed to disasters by quickly and cheaply providing rescuers with the information they need to find people in distress.
GOAL 10 Reduce inequality within and among countries	TARGET 10.7 Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies	INDICATOR 10.7.2 Number of countries with migration policies that facilitate orderly, safe, regular and responsible migration and mobility of people	Drones can be used to support search and rescue of migrants, refugees and internally displaced persons at sea, for example those who find themselves in difficulty crossing the Mediterranean Sea.
GOAL 11 Make cities and human settlements inclusive, safe, resilient and sustainable	TARGET 11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	INDICATOR 11.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	Drones can help to reduce the number of deaths, missing persons and directly affected persons attributed to disasters by quickly and cheaply providing rescuers with the information they need to find people in distress.
GOAL 13 Take urgent action to combat climate change and its impacts	TARGET 13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	INDICATOR 13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	

Table 8: SDG goals, targets and indicators to which drones can contribute data and information for emergency response at the coast.

3.7 Disaster assessment and management

Disasters at the coast can arise from storms, erosion, earthquakes, and human activities, such as oil spills. Assessment of the damages is important for planning recovery activities, assessing insurance claims, and increasing the capacity of coastal communities to respond to future events. Drones are commonly used to support these activities. For example, the use of drones to asses post storm coastal erosion and damage to built infrastructure is well documented (e.g. Scarelli *et al.*, 2017; Alliance for Coastal Technologies, 2018; Duo *et al.*, 2018; Laporte-Fauret *et al.*, 2019; Starek *et al.*, 2019). On the southwest coast of France, Laporte-Fauret *et al.* (2019) demonstrated how a consumer grade quadcopter and photogrammetry techniques could be used to monitor post-storm beach and dune erosion. They showed how high-resolution digital surface models, which can be used to measure morphological and sediment volume changes after a storm or winter storm season, could be created from the visible imagery. The quality of their models were found to be sufficient for coastal monitoring, and the authors highlight the fact that drone data can be obtained cheaper, faster, and more efficiently than aerial LiDAR or traditional ground survey techniques. Starek *et al.* (2019) describe similar work for a hurricane impact assessment in Texas USA. They undertook a drone survey using a consumer grade drone following Hurricane Harvey in 2017. Using photogrammetry techniques, they created a digital surface model and compared it with pre-Hurricane LiDAR data to assess beach erosion and damage to infrastructure. This information was provided to the local authority to assist with recovery efforts. The United States Geological Survey (USGS) regularly undertakes similar work (Alliance for Coastal Technologies, 2018). In Emilia Romagna, Italy, Scarelli *et al.* (2017) showed how such work can help to evaluate the effectiveness of different coastal management interventions. They performed pre- and post-winter storm season drone surveys and generated digital surface models using photogrammetry techniques from the images. Comparison of the resulting models showed how different parts of the shoreline responded differently to one another. This could be explained by the beaches' different physical characteristics as well as the different management interventions present, such as 'bulldozer dunes' (man-made dunes) and breakwaters. The authors highlight the usefulness of the low-cost technique for evaluating the effectiveness of these different shoreline protection measures, which can ultimately support local authorities in the development and implementation of ICZM plans. Similar work was undertaken in the same region by Duo *et al*. (2018). They mapped the extent of flooding and beach erosion following an extreme storm in February 2015, also using a consumer-grade drone and photogrammetry techniques, as part of a post-storm damage impact assessment. The authors argue that the techniques used and the resulting information can be used by the municipality for the development and implementation of local risk management plans.

Also in Italy, Trizzino *et al.* (2017) used drone surveys to detect hazards posed by erosion of rocky cliffs, known locally as 'falesie'. Visible drone images were used to create 3D models of the cliffs, which were compared with LiDAR surveys obtained previously. This allowed them to map the fractured fronts of the cliffs in detail along a 1km stretch of coast in Lecce, Southern Italy. Feng *et al.* (2015) showed how drone data could be used to evaluate hazards posed by flooding in urban areas. Using visible drone imagery from a drone survey covering an urban area in China of approximately $10km^2$, they developed an image classification technique that could detect flooded areas (Figure 10). Quick access to this information is essential to efficiently plan flood relief efforts, especially in urban areas. Popescu *et al*. (2017) undertook similar work for a case study in Romania. They highlight that this information can be used by local authorities to distribute funds and by insurance companies to determine payments. Ezequiel *et al.* (2014) described how visible imagery from drone surveys could be used to estimate damages to crops following a typhoon in the Philippines. They developed an image classification technique for identifying damaged coconut plantations after Typhoon Haiyan. This information can be used by the government to evaluate the scale of recovery assistance required. Separately they describe another application for mapping the extent of new fault systems following an earthquake, also in the Philippines (Popescu *et al.*, 2017). This information is important for the evaluation of post-earthquake hazards.

The applications described above exemplify the potential for drones to contribute to more effective ICZM practices in response to disasters at the coast. Table 9 summarises the specific SDG targets and indicators to which drones can contribute data and information in relation to disaster assessment and management at the coast.

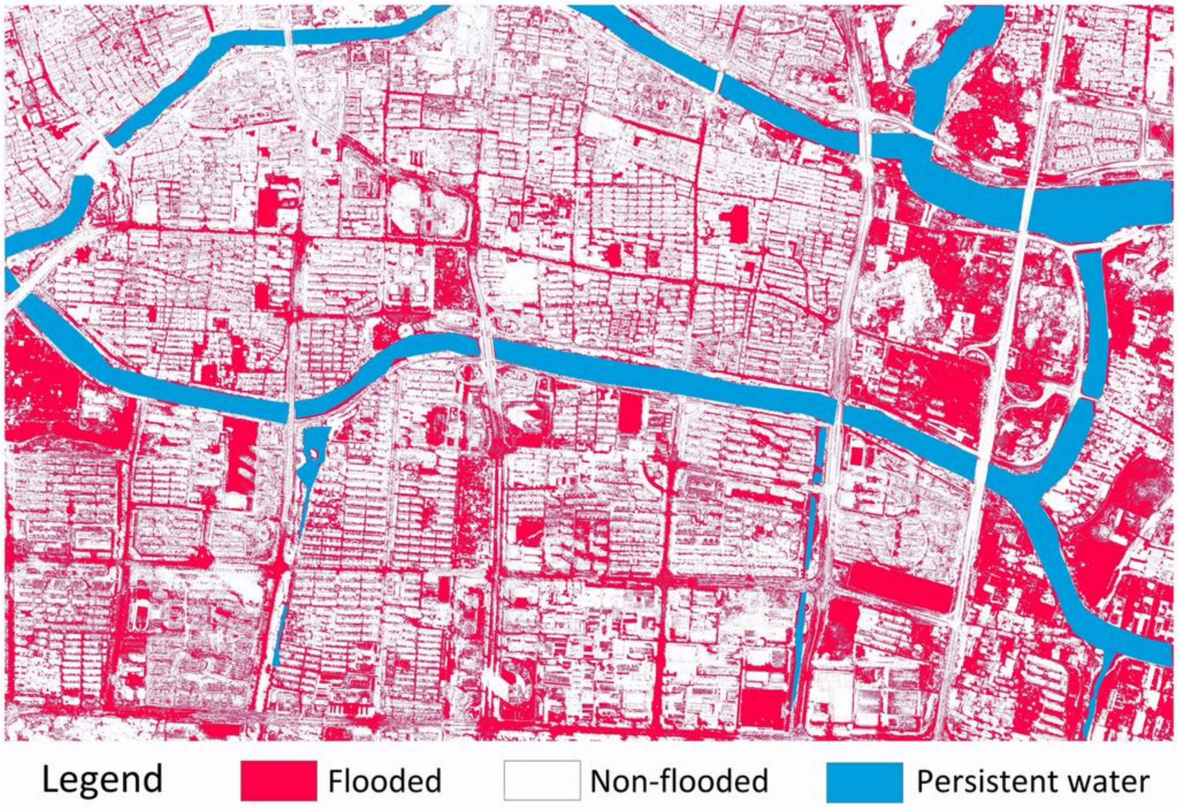

Figure 10: Urban flood map of Yuyao, China generated from drone imagery. [Source: Feng *et al.* (2015)]

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 1 End poverty in all its forms everywhere	TARGET 1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	INDICATOR 1.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population*	Drones can help to quantify damage to dwellings, built infrastructure, agricultural land, and other assets following a disaster, which can also help with estimation of economic losses
		INDICATOR 1.5.2 Direct economic loss attributed to disasters in relation to global gross domestic product (GDP)	
GOAL 11 Make cities and human settlements inclusive, safe, resilient and sustainable	TARGET 11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	INDICATOR 11.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population*	
		INDICATOR 11.5.2 Direct economic loss in relation to global GDP, damage to critical infrastructure and number of disruptions to basic services, attributed to disasters**	
GOAL 13 Take urgent action to combat climate change and its impacts	TARGET 13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	INDICATOR 13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population***	Drones can help to quantify damage to dwellings following climate-related disasters

Table 9: SDG goals, targets and indicators to which drones can contribute data and information in the area of disaster assessment and management at the coast. *Relevant indicator metrics include number of people whose damaged dwellings were attributed to disasters, number of people whose destroyed dwellings were attributed to disasters, and number of people whose livelihoods were disrupted or destroyed, attributed to disasters. **Relevant indicator metrics include direct agriculture loss attributed to disasters, direct economic loss attributed to disasters, direct economic loss resulting from damaged or destroyed critical infrastructure attributed to disasters, direct economic loss to cultural heritage damaged or destroyed attributed to disasters, direct economic loss to other damaged or destroyed productive assets attributed to natural disasters, number of damaged critical infrastructure attributed to natural disasters. ***Relevant indicator metrics include number of people whose damaged dwellings were attributed to disasters, number of people whose destroyed dwellings were attributed to disasters

3.8 Planning and development

Effective planning is a key tenet of integrated coastal zone management and is essential to achieving the sustainable development goals (Burbridge, 1999; West, 2019). A number of studies have highlighted how drones can support planning authorities in the development and implementation of ICZM plans. For example, Scarelli *et al.* (2016) demonstrated how maps generated from drone surveys could be used to identify anthropogenic pressures on a beach/dune system in Brazil. This information could be used to secure funding for local ICZM, especially where local authorities have limited funds/resources to acquire high-quality mapping and monitoring data. Similar work by Scarelli *et al.* (2017) (described in section 3.7 of this report) demonstrates how drone surveys can be used to evaluate the effectiveness of different coastal management interventions, thus supporting local authorities in the development and implementation of evidence-based ICZM plans. Sabetien *et al.* (2019) showed how drone imagery could be used to guide seaweed cultivation planning in the Solomon Islands. They developed a decision support system (DSS) using a GIS technique called spatial multiple criteria analysis (MCA), which allowed them to identify suitable locations for seaweed farming based on multiple, conflicting criteria. Among those criteria was the distribution of the resource and the extent of existing farms, which were mapped from drone imagery. The imagery is further intended to provide useful site information for future farm development, planning and monitoring. The DSS tool, which was developed in collaboration with the Solomon Island Ministry of Fisheries and Marine Resources, will help support the sustainable development of seaweed farming in the Solomon Islands. Work by Brumana *et al.* (2012), described in section 3.5 of this report, demonstrates how drone imagery can be used to support landscape planning by helping to visualise how different development scenarios would impact on waterfront views. Since the images can be easily shared via web-based geoportals, Brumana *et al*. (2012) argue that this can enhance public participation in the planning process. Ezequiel *et al*. (2014) used drone imagery to map land use development trajectories around the Seven Lakes of San Pablo in the Philippines. They contend that such maps can be used to support long-term infrastructure and zoning plans. Similarly, Gallagher and Lawrence (2016) highlight the potential for drone imagery to support sustainable land-use planning in urban environments. For example, high-resolution maps can help to identify and plan the potential re-use of abandoned urban areas within cities. They can also help with planning and management of green and open spaces – e.g. aiding in inventory studies of the health of urban trees to determine stresses, evidence of infestations, disease, the need for addition of new trees, etc. Drones can also support marine spatial planning. Themistocleous *et al.* (2019) used drone imagery in combination with other geospatial data to identify sea and land activities around the ports of Cyprus. This information is essential for the implementation of integrated marine plans in compliance with the European Marine Spatial Planning Directive (2014/89/EU). The relevance of drone technology to the UN sustainable development goals in relation to planning and development at the coast is outlined in table 10.

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 14 Conserve and sustainably use the oceans, seas and marine resources for sustainable development	Target 14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans	None	Drone technology can be used to support marine spatial planning, which will aid in the sustainable management and protection of marine and coastal ecosystems. For example, drones can be used to monitor development activities, such as seaweed farming, which can contribute to the implementation of ICZM and marine spatial plans.
GOAL 16 Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	TARGET 16.7 Ensure responsive, inclusive, participatory and representative decision-making at all levels	None	Drone imagery can be used to enhance public participation in the planning process

Table 10: SDG goals, targets and indicators to which drones can contribute data and information in relation to planning and development at the coast.

3.9 Tourism

Drone imagery and videos are well placed to promote tourism and to facilitate 'virtual tourism' - the experience of visiting a place through digital media without physically being present in that place (Kitonsa *et al.*, 2018). Several companies with expertise in drone photography/videography and virtual reality (VR) imaging technology are now offering to create customised, sometimes interactive, virtual tours for businesses in the tourism sector (3deep, 2020; e.g. Drone View, 2020; Virtual Reality Tour Guys, 2020). The tours can be simply made up of images or video footage or they can be more complex, for example offering visitors the chance to explore an area in 3D with supplementary educational information embedded in the tour (Mirk and Hlavacs, 2014). The tours can be delivered via the web for viewing on a computer or mobile device or even using VR goggles for a more immersive experience (Rutkin, 2015). In Ireland, local authorities are using drone imagery and footage for marketing national brands such as the Wild Atlantic Way, Ireland's Ancient East and Dublin: A Breath of Fresh Air (DHLGH, 2017). Besides being used for marketing and promotion, drone imagery and footage can help to limit visitors to certain areas threatened by excessive human activity, thereby contributing to more sustainable tourism practices. For example, the high number of visitors to the South Ari atoll Marine Protected Area (SAMPA) in the Maldives is posing a threat to resident marine species (Femmami, 2019). Interactions with an increasing number of boats are causing injury to a high proportion of local whale sharks (Allen, 2018). In addition, overcrowding threatens the safety of swimmers and negatively affects visitors' satisfaction. Femmami (2019) argues that drones can be used to help alleviate these problems. For example, drones can be used by rangers to perform aerial surveillance operations, giving them the information they need to disperse tour operators among a greater number of sharks, thereby limiting interactions with boats as well as the potential danger to swimmers.

'Virtual tourism' has perhaps never been more relevant than in the time of coronavirus (Katanich, 2020). In Ireland, Virtual Visit Tours uses a combination of ground and drone imagery to create 360 degree immersive media tours of popular tourist destinations (Virtual Visit Tours, 2020; Figure 11). The tours have been featured as destinations for virtual visitors who cannot physically travel to the island or site as a result of travel restrictions or temporary closure due to Covid-19 (Romano, 2020). Other examples of virtual tourism include a virtual drone tour of Pompeii (Osanna, 2020) and tours of (mostly UK-based) tourist destinations created by 3deep (3deep, 2020).

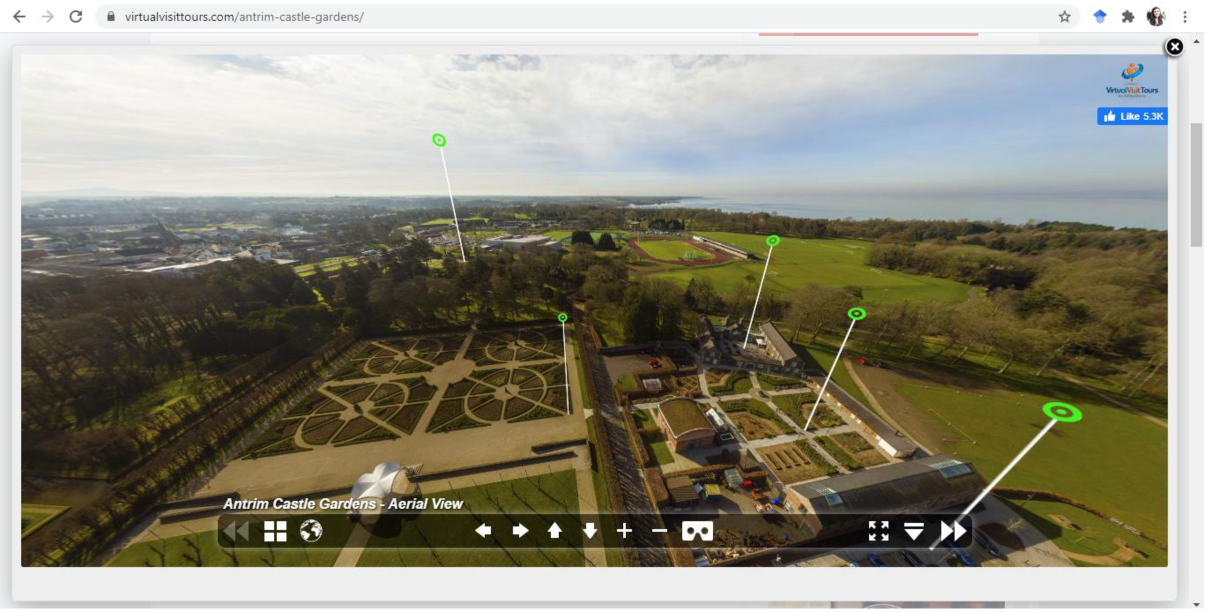

Figure 11: Screenshot of a virtual tour of Antrim Castle Gardens. The functions of this web-based viewer, created and hosted by Virtual Visit Tours, are similar to those in Google Earth and Google Street View, allowing visitors to explore the site from the air or the ground. [Source: Virtual Visit Tours (2020)]

Traditionally, virtual tourism was seen as a way to promote a location to attract visitors, usually commissioned by hotels, tourist sites, and other businesses in the tourism industry, but in the last few months it has emerged as an entertaining and educational way of visiting far-flung places that are temporarily off-limits. Such tours can be monetised, for example by generating ad revenue from YouTube and other social media sites. The revenues can potentially be used by local coastal communities to promote the sustainable development of the tourism sector. The relevance of drone technology to the UN sustainable development goals in relation to tourism at the coast is outlined in table 11.

SDG Goal	Target	Indicator	Relevance of drone technology
GOAL 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	TARGET 8.9 By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	INDICATOR 8.9.1 Tourism direct GDP as a proportion of total GDP and in growth rate	Drone imagery/footage can be used in 'virtual tourism' products, which can be monetised, providing a source of income for local businesses, and the revenues can potentially be used by local coastal communities to promote the sustainable development of the tourism sector.
GOAL 11 Make cities and human settlements inclusive, safe, resilient and sustainable	TARGET 11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage	None	Drone technology can help to limit the impacts of tourism on cultural and natural heritage sites at the coast, for example, by helping to deliver 'virtual tourism' as an alternative to physical visits to threatened sites
GOAL 12 Ensure sustainable consumption and production patterns	TARGET 12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	INDICATOR 12.b.1 Number of sustainable tourism strategies or policies and implemented action plans with agreed monitoring and evaluation tools	Drone imagery/footage can be used in 'virtual tourism' products, which can create jobs and promote local culture and products.

Table 11: SDG goals, targets and indicators to which drones can contribute data and information in relation to tourism at the coast.

4. Conclusion

The potential for drones to contribute data and information to support ICZM and sustainable development at the coast is appreciable. The technology can help local authorities, provided they are aware of its capabilities, as well as its limitations. This report demonstrates several innovative applications across nine key areas, although it is by no means exhaustive. The relevance of drone technology to the SDGs has also been explored, and clearly it offers potential for measuring progress toward the goals as well as supporting their achievement. This should be of interest to local authorities given the cost effectiveness (against alternative technologies) and their role in contributing to the SDGs at the local level.

As drone technology develops, new applications will no doubt emerge. It is crucial at this point that local authorities who wish to employ drone technology have a policy or strategy in place that deals specifically with the use of drones (Gee, 2019) and have suitably trained staff to undertake survey and/or data analysis activities. There are three options for local authorities who wish to employ drone technologies for ICZM activities:

(1) Undertake data acquisition and processing internally
(2) Outsource data acquisition and processing
(3) A combination of the above

The implementation of the first option – e.g. the development of a dedicated drone department – is complex, costly, and requires significant resources. Outsourcing may be preferred to limit costs and complications. This is not to say that some activities cannot be undertaken by local authorities. As we've seen in this report, Irish local authorities have been effective in using drones to tackle illegal dumping. However, for more complex tasks, time and money can be saved by employing experts.

At a minimum, local authorities should be aware of the potential applicability of drone technology so that it can be evaluated alongside alternatives for the practical implementation of ICZM.

Appendix I: Definitions

Active sensor	A sensor that emits its own energy and records the response from the physical environment. Microwave and LiDAR sensors are examples of active sensors. Passive sensors, on the other hand, record energy emitted or reflected by the physical environment. Digital cameras are examples of passive sensors, in that they record the light that is reflected by an object or surface.
Blue carbon	Carbon dioxide that is removed from the atmosphere by coastal ecosystems, primarily mangroves, saltmarshes, and seagrass. These ecosystems sequester and store a large amount of carbon, and therefore play an essential role in regulating the Earth's climate.
Blue growth	A loose term that refers to the environmentally sustainable growth of the marine and maritime economy (Eikeset *et al.*, 2018). In Europe, "Blue Growth" is the European Union's long-term strategy to support sustainable growth in the marine and maritime sectors as a whole.
False colour image	An image that depicts an object or surface in colours different to that of a traditional photograph (or true colour image). They illustrate the amount of reflectance in different parts of the electromagnetic spectrum, thus allowing us to visualize wavelengths that the human eye cannot see, such as near infrared. These are also sometimes called pseudo-colour images. Imagery captured by thermal sensors, for example, is displayed as a false colour image, whereby warmer objects stand out against cooler ones.
Georeferencing	The process of assigning real world geographic coordinates to an image so that it can be referenced against other geographic data. Drone imagery captured for survey purposes must be georeferenced. This can be achieved in a number of ways, for example by using targets placed in the field during a survey whose coordinates are recorded using a GPS or by georeferencing the image to an existing image that already has embedded geographic information (*e.g.* from referenced satellite imagery). Georeferencing is usually done using GIS or other mapping software packages, such as ArcGIS Pro or Pix4D.
GIS	Geographical Information Systems (GIS) is a framework for collecting, managing, and analyzing geographical data. GIS software packages, such as ArcGIS Pro, are commonly used to manage, analyse, and share drone data. These can be used, for example, to georeference and orthorectify imagery, create maps, generate digital elevation models, and to detect land use changes over time.
Ground Control Points	Points on the ground used to georeference drone imagery. These are usually taken as the centre of circular or square targets placed on the ground during a survey whose position is recorded on the ground using a GPS. The points can then be identified in the imagery and assigned those positional coordinates. This is usually performed in GIS or other mapping software packages, such as ArcGIS Pro or Pix4D.
Hyperspectral sensor	Hyperspectral sensors record energy reflected in many narrow bands of the electromagnetic spectrum, often outside of the visible portion. They are useful for identifying objects on the ground with unique reflectance characteristics, such as phytoplankton, which can be difficult to distinguish using visible or multispectral imagery. Hyperspectral sensors differ from multispectral sensors in that they record reflectance in many more and much narrower bands of the electromagnetic spectrum. For some applications, features on the ground can be more easily identified (mapped) based on their reflectance characteristics in such bands.

ICZM	Integrated coastal zone management is a holistic and integrated approach to the management of coastal areas. It seeks to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics. It is based on the principles of sustainability, active stakeholder engagement and cooperation, evidence-based decision making, and the integration of all relevant policy areas, sectors, and levels of administration across both time and space (EEA, 2000). While there are no statutory requirements in the EU to implement ICZM, there are synergies between the approach and the EU directive on Marine Spatial Planning (Directive 2014/89/EU).
LiDAR	Light Detection and Ranging (LiDAR) is an active remote sensing technology that can be used to create accurate and detailed elevation models. Traditionally flown on a piloted aircraft, LiDAR sensors are increasingly being flown on drones. Such surveys can produce more detailed datasets and are generally cheaper and safer to obtain than those obtained from piloted aircraft.
Multispectral sensor	Multispectral sensors (or cameras) record energy reflected in several bands of the electromagnetic spectrum, including those than cannot be seen by the naked eye, such as the near infrared. They are useful for identifying objects on the ground with unique reflectance characteristics, such as different types of vegetation or land cover, which can be difficult to distinguish from visible imagery alone. For some applications, features on the ground can be more easily identified (mapped) based on their reflectance characteristics in these different bands.
NDVI	The normalised difference vegetation index (NDVI) is an indicator of vegetation health based on reflectance characteristics in the red and near infrared bands of the electromagnetic spectrum. It can be calculated for each pixel of an image using the following equation: $$NDVI = \frac{NIR - RED}{NIR + RED}$$ Where: NDVI = normalised difference vegetation index (unitless) NIR = reflectance in the NIR portion of the spectrum RED = reflectance in the red portion of the spectrum The resulting image can be displayed as a false colour image that highlights healthy versus unhealthy vegetation. Often used for agricultural applications, it can also be used for ecological resource assessments and habitat mapping.
Orthorectification	Orthorectification is the process of removing geometric distortions caused by terrain and the angle at which an image is acquired. It can be thought of as the process of 'stretching' an image such that the scale becomes uniform. This is an essential processing step for drone imagery that is to be used for survey purposes, because uncorrected images will not produce accurate measurements. This can be done in GIS or other mapping packages, such as ArcGIS Pro and Pix4D.
Orthomosaic	An orthomosaic is a collection of orthorectified images stitched together to create a single, seamless image.
Passive sensor	Passive sensors record energy emitted or reflected by the physical environment. Digital cameras are examples of passive sensors, in that they record the light that is reflected by an object or surface. Thermal sensors are also passive sensors, in that they record heat emitted by a surface. These are different from active sensors, which emit their own energy.

Photogrammetry	Photogrammetry is the science of extracting 3D information from overlapping 2D photographs taken from different vantage points. Aerial photogrammetry software packages match pixels from the overlapping imagery and use triangulation to calculate 3 dimensional object coordinates. Commonly used packages for drone survey data include Pix4D and Agisoft Metashape.
PPK geolocation	A method for geolocating drone imagery that involves correcting the trajectory after the survey using a precisely located local base station.
Radiometric resolution	The ability of a sensor to distinguish differences in light intensity or reflectance.
Remote sensing	The process of collecting information about an object or surface without physically being in contact with it. Remote sensing platforms include satellites, aircraft and drones.
RTK GPS/GNSS	Real-time kinematic global positioning systems or global navigation satellite systems provide highly precise information about the location of a point on the Earth's surface. For precise georeferencing of drone imagery, coordinates can be obtained using an RTK GPS. These coordinates are known as ground control points.
Spatial multiple criteria analysis	Spatial multiple criteria analysis (MCA) is a GIS technique for assessing multiple and often conflicting criteria across a geographical area. It is often used for site suitability assessments and risk assessment studies. It involves overlaying multiple layers of geographical information to produce a single layer illustrating where desirable (or undesirable) criteria overlap.
Spatial resolution	Spatial resolution is a measure of the smallest object that can be resolved by a sensor. It can be defined as the size of a single pixel on the ground (sometimes referred to as the ground sampling distance, or GSD).
Spectral resolution	Spectral resolution refers to the ability of a sensor to resolve features in the electromagnetic spectrum. The higher the spectral resolution, the narrower the wavelength band. Hyperspectral sensors have higher spectral resolution than multispectral sensors.
Spectral signature	The unique variation in reflectance (or emittance) of an object with respect to wavelengths on the electromagnetic spectrum. Different surfaces or objects reflect different amounts of energy at different wavelengths. As a result, it is possible to distinguish, for example, between different land cover types or vegetation types. This allows for the creation of maps that can help identify the geographical coverage of features of interest on the ground.
Structure from Motion	Structure from Motion (SfM) is a photogrammetric technique for creating a 3D model from 2D images. SfM does not require ground control points to create a 3D model. The resulting models are used more for visualisation purposes rather than to generate survey grade models.
Sustainable development	Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).
Temporal resolution	Where multiple images are undertaken at regular intervals, temporal resolution refers the period of time between which the images were acquired.
True colour image	An image that depicts an object or surface in colours similar to what we might see with our own eyes. True colour images are composites of reflectance recorded in the red, green, and blue portions of the electromagnetic spectrum, thus are sometimes referred to as RGB images.

	Traditional photographs, including those obtained from the cameras aboard many consumer-grade drones, are true colour images.
Visible image	See *true colour image*

Appendix II: Guidance materials on drone use from national aviation authorities

Country	National Aviation Authority	Link to guidance material
Finland	Finnish Transport Safety Agency	https://www.droneinfo.fi/en
Iceland	Icelandic Transport Authority	https://www.icetra.is/aviation/drones/
Ireland	Irish Aviation Authority	https://www.iaa.ie/general-aviation/drones
United Kingdom	UK Civil Aviation Authority	https://www.caa.co.uk/Consumers/Unmanned-aircraft-and-drones/

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