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The Use of Earth Observation and Machine Learning for Industrial and Waste Crime Identification and Prevention

Authors: Zane Ferch, Steve Coughlan, Charlotte O'Kelly and Sinead McGlynn

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing

> Large-scale industrial, waste and petrol storage activities;
> Urban waste water discharges;
> The contained use and controlled release of Genetically Modified Organisms;
> Sources of ionising radiation;
> Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

National Environmental Enforcement

> Audit and inspection of EPA licensed facilities;
> Drive the implementation of best practice in regulated activities and facilities;
> Oversee local authority responsibilities for environmental protection;
> Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
> Assess and report on public and private drinking water quality;
> Coordinate a network of public service organisations to support action against environmental crime;
> Prosecute those who flout environmental law and damage the environment.

Waste Management and Chemicals in the Environment

> Implement and enforce waste regulations including national enforcement issues;
> Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
> Develop and implement the National Waste Prevention Programme;
> Implement and report on legislation on the control of chemicals in the environment.

Water Management

> Engage with national and regional governance and operational structures to implement the Water Framework Directive;
> Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

Climate Science & Climate Change

> Publish Ireland's greenhouse gas emission inventories and projections;
> Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
> Support National, EU and UN Climate Science and Policy development activities.

Environmental Monitoring & Assessment

> Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
> Produce the State of Ireland's Environment and Indicator Reports;
> Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
> Oversee the implementation of the Environmental Noise Directive;
> Assess the impact of proposed plans and programmes on the Irish environment.

Environmental Research and Development

> Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
> Collaborate with national and EU environmental research activity.

Radiological Protection

> Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
> Assist in developing national plans for emergencies arising from nuclear accidents;
> Monitor developments abroad relating to nuclear installations and radiological safety;
> Provide, or oversee the provision of, specialist radiation protection services.

Guidance, Awareness Raising, and Accessible Information

> Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
> Promote the link between health and wellbeing, the economy and a clean environment;
> Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
> Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

> Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

epa Research

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Identifying pressures

Waste crime and environmentally damaging forms of industrial non-compliance or negligence are damaging to the environment and human health, have an impact on an area's aesthetics, and are often extremely costly to clean up. These crimes are often carried out because they are easy to commit and can be very profitable for the perpetrator, who can be hard to catch . Waste crime can occur anywhere and at any scale, from a roadside bin bag left by a single person to the pollution of entire waterbodies by industrial actors.

Figuring out when, how frequently, or if an environmental crime has occurred at all, is not simple. This means that perpetrators may be left to commit waste crimes for extended periods of time, and waste crime sites may grow bigger and more difficult to remediate. The effects of pollution may also linger in the environment and have an impact on human health for as long as the waste is left in situ. Therefore, enforcement authorities have incentives to minimise waste crime and industrial non-compliance by detecting and reacting to it as quickly as possible.

Informing policy

Detecting and reacting to potential waste and environmental crime and industrial non-compliance as quickly as possible has large financial and societal implications for enforcement authorities. The damage that these relatively easy-to-commit crimes can incur on human and environmental health, and the costs associated with remediating these issues, represent a problem that becomes more difficult and more costly to resolve the longer that it is left unaddressed.

Currently, waste crime and industrial non-compliance is discovered either through public complaints or site visits by inspectors. These are, and will always remain, essential tools for enforcement authorities, but they have limitations. Public complaints are ineffective in remote or hard-to-access areas where the public may not be aware of an issue. Site inspections are the primary tool for gathering evidence for cases of waste crime or industrial non-compliance, but they are administered either randomly, to sites with known issues, or to sites where complaints are made.

This research aims to provide enforcement authorities with another way of generating reports for more efficient inspections of key sites.

Developing solutions

Three service recommendations were proposed, aimed at different user groups with various funding capabilities. The most comprehensive recommended service would utilise both publicly and commercially available Earth observation data in conjunction with records of previous waste crime and industrial non-compliance incidents to build a machine learning algorithm for detecting such crimes at a national scale.

Additionally, when a potential waste crime is detected in publicly available satellite data, a report would be made available detailing the confidence of the machine learning model and any commercially available satellite imagery that may be useful for a deeper analysis of the area. This provides enforcement authorities with the opportunity to react to potentially unknown waste crimes in near real time, or allow them to gather more information on waste crime.

Finally, commercial data have higher spatial and temporal resolution, giving enforcement authorities the opportunity to go back through the archive to detect exactly what happened at a specific site, when and where. Validation of the model, either by deeper analysis or by site visits by personnel, are used to further improve the model's future performance.

EPA RESEARCH PROGRAMME 2021–2030

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Prepared for the Environmental Protection Agency

by

TechWorks Marine

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Waste crime is broadly defined as the illegal or unauthorised handling, disposal, storage or trafficking of waste. While waste crimes generally include both small-scale crimes and large-scale industrial non-compliance, for the purpose of this report waste crime and industrial non-compliance will be referred to separately to reflect the difference in scale and potentially unintentional nature of non-compliance. Waste and environmental crime costs millions in annual tax revenues forgone, damages the environment and poses a risk to human health. Illegal waste presents governments with a wide range of risks that have prompted demands for cost-effective, efficient monitoring and mapping solutions to support improved management outcomes. The enforcement of unauthorised waste disposal is a priority action for regulators, according to the EPA's state of the environment report, *Ireland's Environment – An Integrated Assessment 2020*.[1] The EPA and local authorities have statutory responsibilities for authorising and enforcing proper waste collection and management activities. The EPA's waste enforcement approach is governed by a compliance and enforcement policy. Eleven prosecutions of waste and industrial licensees have concluded with convictions since 2016, one brought by the Director of Public Prosecutions. The charges in these cases included exceedance of emission limits and failure to notify the appropriate authorities of incidents. The ubiquity and scale of waste crime is immense, with approximately 73,000 waste- and litter-related complaints received by local authorities in 2021 and 68% of enforcement staff assigned to waste. For many years, disposal to landfill was the primary method for managing waste in Ireland, and there is a significant ongoing cost to the state for the remediation and monitoring of the 611 regulated and unregulated sites, which includes four active landfills. Ireland has limited national capacity to manage the waste it generates, so increased recycling and reuse of waste outputs is crucial.

Remote sensing technologies, such as satellites and drones, have the potential to improve governments' ability to monitor, detect and prevent environmental crimes and industrial non-compliance. This includes long-term site monitoring to detect changes. Remote sensing technologies and methodologies can be used to monitor and map activities such as illegal dumping (increase in size of landfill area or large areas of illegally dumped waste) and illegal burning of waste, non-compliance at licensed facilities across the industrial, food processing and agricultural sectors, and the extent of illegal extraction of peat in bogland areas. Data from satellites and drones can provide critical information to inform targeted active surveillance operations and cost-effective remediation activities.

Space-borne remote sensing instruments can deliver reliable repeat-coverage datasets that can be further processed and analysed using specialised tools and techniques to provide useful and actionable information on environmental crime. High- to medium-resolution optical satellite imagery can be used to obtain information on the location and distribution of environmental crimes such as illegal waste sites. Thermal satellite imagery can be used to identify the illegal burning of waste, as well as increases in land surface temperature due to bacterial activity in waste sites. Synthetic aperture radar satellite imagery can be used to detect changes on the surface of peatland, indicating extraction works (both legal and illegal), oil, sewage and chemical spills in lakes, rivers and coastal zones, and changes in land topography, indicating illegal burial of waste. Drone technology has the ability to provide very-high-resolution on-demand optical and thermal imagery of environmental crimes, as well as video footage of illegal activities in progress. In this report, we undertake a comprehensive review of the current capabilities and applications of orbital satellite sensors (optical, thermal and radar), current drone technology and machine learning

1 https://www.epa.ie/our-services/monitoring--assessment/assessment/irelands-environment/state-of-environment-report-/ (accessed 5 June 2023).

techniques in the area of waste crime and industrial non-compliance detection and prevention. There are gaps in knowledge and methodologies, for example using Earth observation data to measure industrial atmospheric pollutants. The Earth observation sector is developing rapidly, and new satellites are being launched yearly, improving the quality and frequency of both publicly available and commercial services.

1 State of Current Earth Observation Technology

1.1 Optical Satellites for Earth Observation

Optical remote sensing makes use of visible, near-infrared (NIR) and short-wave infrared (SWIR) instruments to form images of the Earth's surface by detecting the solar radiation reflected from targets on the ground. Optical remote sensing depends on the Sun as the sole source of illumination. Different materials reflect and absorb radiation differently depending on the wavelength. Thus, targets can be differentiated by their spectral reflectance signatures in the remotely sensed images. Optical remote sensing systems are classified as either multispectral or hyperspectral, depending on the number of spectral bands used in the imaging process.

In a multispectral imaging system, the sensor records multiple images corresponding to radiation within a narrow wavelength band. The result is a multi-layer image that contains both brightness and spectral (colour) information on the targets being observed. Multispectral sensor instruments are found on many of the well-known Earth observation (EO) satellites currently in orbit (e.g. Landsat 8, Sentinel-2, WorldView-2). Hyperspectral imaging systems (also known as imaging spectrometers) acquire images in approximately one hundred or more contiguous spectral bands. The precise spectral information contained in a hyperspectral image enables better characterisation and identification of targets. Hyperspectral images are useful in fields such as precision agriculture (e.g. monitoring the type, health, moisture status and maturity of crops) and oceanography (e.g. monitoring of phytoplankton).

Each optical remote sensing sensor has its own technical characteristics in terms of temporal, spatial, spectral and radiometric resolution. Depending on the specific requirements of a project, such as study area size, spatial and temporal resolution required, data availability or thematic specifications, multi- or hyperspectral sensors can be applied. There are hundreds of optical EO satellites currently in orbit, operated by government agencies of one or more countries or by private companies that build, operate and maintain their own satellites for commercial purposes. For the purposes of this research, the focus will be on the data from optical satellite platforms, which are readily available and easily accessible, and their potential for use in monitoring waste crime.

When bands are displayed together in a single image, it is referred to as a composite image. Composite images consisting of two or more bands are often displayed in colour. The most common form of composite image is created using the red, blue and green bands, forming an image that looks like a photograph – a "true colour" image. However, it is also possible to create various forms of "false colour" image, using different data bands and highlighting features that may not be visible to the human eye.

True colour composites resemble what a human eye may see from the same perspective. In the true colour image of Galway city (Figure 1.1A), recognisable features such as urban areas and water bodies are clear. Peat, fallow fields and coastal habitats are also visible, but the viewer may require contextual clues to distinguish them. Vegetated areas, while conspicuously green, are not as easy to distinguish, for example telling a field from a forest. Furthermore, small features such as rural houses may take up only a few pixels and therefore do not stand out.

A popular form of false colour composite image, seen in Figure 1.1B, is the "colour infrared", composed of three bands, in this case Sentinel-2's NIR in the red channel, red in the green channel, and green in the blue channel. The colour infrared composite image is often used for assessing vegetation. Plants absorb red light but reflect NIR and green light, resulting in vegetated areas that range from red to brown. Areas that are a deeper red are more densely vegetated, and areas that are brown indicate that the vegetation is in poor health. Urban areas, lacking in vegetation, show up as a bright blue or grey, creating a strong contrast with the red vegetated areas. Turbid and shallow water is also easy to spot, since it is displayed as a light blue in an otherwise deep blue water body. While shallow water is clearly distinguished, some detail of surface water quality is lost compared with the true colour composite image.

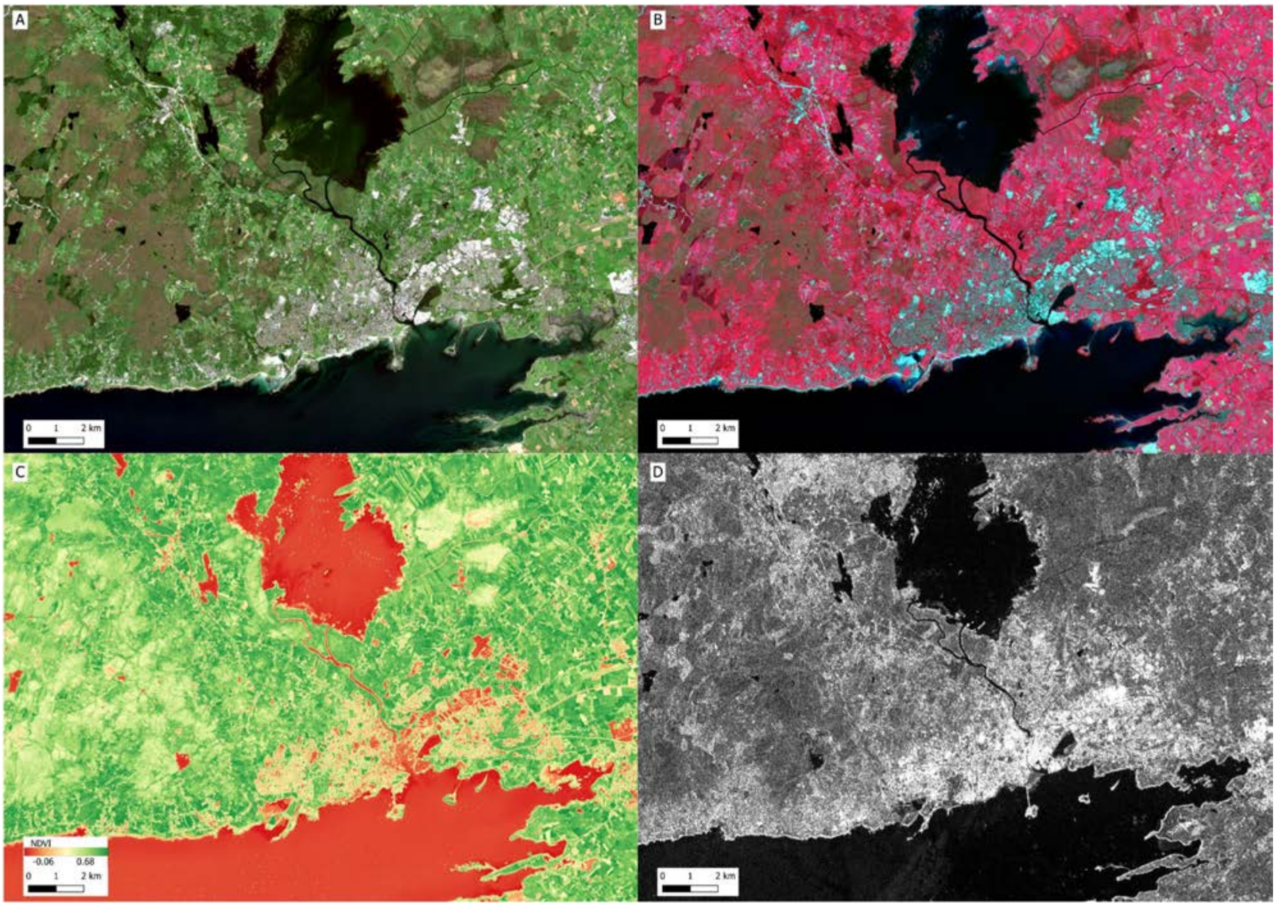

Figure 1.1. Maps of Galway using publicly available data from Sentinel-1 and -2. (A) True colour composite image (Sentinel-2). (B) False colour composite image (Sentinel-2). (C) Normalised Difference Vegetation Index (Sentinel-2). (D) Synthetic aperture radar image (Sentinel-1).

While multiple bands can be overlaid to create composite images, individual bands can also be used in mathematical equations to highlight differences. Each band is stored as a grid of data points known as a raster, and mathematics using these bands is known as raster maths. A common application of raster maths is the NDVI, or Normalised Difference Vegetation Index, which is a tool used to measure the health and abundance of vegetation. In Figure 1.1C, an NDVI created from Sentinel-2 data, urban areas and water are seen as red, while fields are green. However, not all water bodies are completely red: for example, the southern shore of Lough Corrib (the water body shown in red to the north) has small areas of yellow, which indicate aquatic vegetation.

A comprehensive review of current satellite platforms can be found on the TechWorks Marine website (https://techworks.ie/services/earth-observation/). This report provides a summary of that information.

1.1.1 Publicly available optical satellites

The two publicly available optical satellite platforms are the Sentinel-2 mission and the Landsat mission. The Sentinel-2 mission consists of a constellation of satellites operated by the European Space Agency (ESA) and is part of the European Union's Copernicus programme. The EO programme is coordinated and managed by the European Union Agency for the Space Programme in partnership with ESA. The satellite systematically acquires optical imagery at high spatial resolution (10 m, 20 m, 60 m) over land and coastal waters. The Sentinel-2 mission currently comprises a constellation of two polar-orbiting satellites, Sentinel-2A and Sentinel-2B, placed in the same Sun-synchronous orbit, phased at 180° to each other. A third satellite, Sentinel-2C, is currently undergoing testing in preparation for launch in 2024.

The Sentinel-2 satellites each carry a single multispectral instrument with 13 spectral channels in the visible, NIR, and SWIR spectral ranges at a spatial resolution of 10 m, 20 m and 60 m (depending on band). The 10-m spatial resolution allows continued collaboration with the Landsat 8 mission and the combination of Sentinel-2 data with historical images to build long-term time series. A wide swath width (290 km) and high revisit time (10 days at the equator with one satellite and 5 days with two satellites, and 2–3 days at mid-latitudes with two satellites) provide reliable repeat coverage.

The Landsat programme is the longest-running EO programme, consisting of a series of optical/infrared remote sensing satellites for land observation. The programme was first started by the National Aeronautics and Space Administration (NASA) in 1972, then turned over to the National Oceanic and Atmospheric Administration (NOAA) after it became operational. All data are in the public domain and are distributed free of charge by the United States Geological Survey (USGS). Landsat 8 and 9 are the two active Landsat satellites, providing similar data. The Landsat satellites provide panchromatic imagery at 15-m resolution and multispectral imagery at 30- to 100-m resolution (depending on band). Landsat 8 has a revisit time at mid-latitudes of approximately 6 days.

1.1.2 Commercially available optical satellites

Pléiades and SPOT

Pléiades is a very-high-resolution optical constellation composed of two satellites, Pléiades-1A and Pléiades-1B, launched in 2011 and 2012, respectively. The constellation is operated by the French Space Agency, Centre national d'études spatiales (CNES). The high-resolution imager on board the Pléiades constellation delivers very high optical resolution (0.5 m, 0.7 m, 2 m) imagery with a swath width of 20 km. Designed as a dual civil/military system, Pléiades meets the imagery requirements of European defence as well as civil and commercial needs. In 2022, a new constellation named Pléiades Neo was launched, consisting of four satellites with 0.3-m resolution, improving the frequency and resolution of previous Pléiades data. Pléiades offers a daily (every 24 hours) or better revisit capability over any point on the globe.

The Pléiades satellites also share the same orbital plane as the SPOT 6 and 7, forming a larger constellation with four satellites 90° apart from each other. SPOT 6 and 7 provide panchromatic (at 1.5-m resolution) and multispectral (at 6-m resolution) imagery with a swath width of 60 km and have the capacity to acquire up to 3 million km^2 of imagery daily.

Maxar

Maxar Technologies operates four very-high-resolution optical satellites: GeoEye-1, WorldView-1, WorldView-2 and WorldView-3. The GeoEye-1 satellite collects panchromatic images at 0.41-m and multispectral images at 1.65-m resolution. The satellite can collect up to 350,000 km^2 of multispectral imagery per day and can revisit any point on Earth approximately once every 3 days. WorldView-1 carries a panchromatic imaging system capable of providing 0.5-m resolution imagery. WorldView-1 does not carry a multispectral sensor. With an average revisit time of 1.7 days, WorldView-1 is capable of collecting up to 750,000 km^2 of panchromatic imagery per day. WorldView-2 provides panchromatic imagery at 0.46-m resolution and eight-band multispectral imagery at 1.84-m resolution. WorldView-3 provides panchromatic imagery at 0.31-m resolution, eight-band multispectral imagery at 1.24-m resolution, SWIR imagery at 3.7-m resolution, and CAVIS (clouds, aerosols, vapours, ice and snow) data at 30-m resolution. WorldView-3 is the industry's first multi-payload, super-spectral, high-resolution commercial satellite.

Planet Labs

Planet Labs owns and operates SkySat, a constellation of sub-metre-resolution EO satellites providing very-high-resolution panchromatic and multispectral images and high-definition (HD) video. The SkySat satellites are based on the CubeSat concept and make use of inexpensive automotive-grade electronics and fast commercially available processors. There are currently 21 satellites in the SkySat constellation, allowing an approximate revisit frequency of six to seven times per day at mid-latitudes. This can be increased to 12 times per day at certain latitudes. SkySat can provide panchromatic imagery at a spatial resolution of 0.9 m, making it the smallest and cheapest satellite in orbit capable of such high-resolution imagery. The multispectral sensor collects data in blue (450–515 nm), green (515–595 nm), red (605–695 nm) and NIR (740–900 nm) spectral bands at 2-m resolution.

1.2 Synthetic Aperture Radar Satellites for Earth Observation

Unlike multispectral imagery, synthetic aperture radar (SAR) imagery records not light but radar, which is not obstructed by atmospheric conditions. SAR imagery records multiple bands, but instead of different bands corresponding to different wavelengths (as in multispectral imagery), SAR bands correspond to the polarisation of the radar wave. SAR instruments emit radar signals with either vertical (V) or horizontal (H) polarisation, and then measure the backscatter of either V or H polarisation. Not all SAR systems emit or measure both. Although composite images of SAR bands are sometimes used for visualisation purposes, it is common for only one band to be shown in black and white. For Sentinel-1, the VV band is the more data rich, and some details can be seen on the water in Figure 1.1D: these are not visible in the VH band. The different shades result from the backscatter qualities of different surfaces. Urban areas are full of hard and smooth surfaces that reflect the most signal back to the satellite. Vegetation reflects less signal than urban areas, but different types of vegetation have different backscatter qualities. Water has the lowest backscatter and appears black, but waves caused by rough weather reflect the signal and are often visible.

1.2.1 Publicly and commercially available SAR instruments

Airborne and space-borne SAR instruments are capable of producing very-high-resolution images of the planet's surface and have a large range of applications. SAR imagery is employed in the fields of geography, oceanography, glaciology and geology. The technology is applied to the monitoring of civil infrastructure projects, such as dams, bridges and roads, and of urban growth. SAR imagery is useful in environmental monitoring such as oil spills, flooding, wetlands and coastal erosion. SAR imagery is also heavily used by the military around the world for strategic policy and tactical assessment. Beyond our own planet, SAR imagery has been used to map the surfaces of the Moon, Mars, Venus and the many moons of Jupiter and Saturn. SAR imagery's principal advantage is its ability to provide regular, reliable and automated change detection, without interference from clouds or darkness.

The applications of SAR imagery are numerous, but only in recent years has the technology become more mainstream and accessible. Traditionally, SAR technology was classified, restrictively expensive and/or solely within the purview of the military and national space agencies. Furthermore, as SAR imagery measures microwaves rather than visible light, the data require complex processing methodologies and are not easily interpreted or user friendly. However, recent advances in SAR sensor technologies and processing methodologies have dramatically lowered the costs involved and made interpretation and widespread use of the data possible for an ever-expanding range of applications. There is a plethora of SAR satellites currently in orbit, operated by government agencies of one or more countries or by private companies that build, operate and maintain their own satellites for commercial purposes.

Sentinel-1

The Sentinel-1 satellites are part of the Copernicus programme, the European Union's EO programme coordinated and managed by the ESA. The Sentinel-1 mission is composed of a constellation of two satellites, Sentinel-1A and Sentinel-1B, sharing the same orbital plane. Sentinel-1B has been non-functional since December 2021, and a replacement, Sentinel-1C, is planned. Sentinel-1 satellites carry a C-band SAR instrument with a spatial resolution as fine as 5 m and a swath width of up to 400 km, depending on the mode of operation. The two satellites take regular SAR measurements of the planet's surface, jointly covering the entire planet every 6 days, depending on latitude. Sentinel-1C and -1D are currently in development, with 1C set for launch in 2023, ensuring the continuation of the mission into the future, as well as promising a further reduction in revisit times.

RADARSAT

RADARSAT is a Canadian EO satellite programme overseen by the Canadian Space Agency (CSA).

The programme currently consists of four satellites: RADARSAT-2 and three more satellites in a constellation called the RADARSAT Constellation Mission (RCM). All four satellites use a C-band SAR instrument for image acquisition. As RADARSAT-2 is approaching the end of its expected operational life, the RCM was launched to provide continuing C-band SAR data, improve the revisit frequency and area coverage, and reduce the risk of service interruption associated with one satellite. The C-band SAR instrument on board the satellites has several modes of operation, the most common and relevant being fine (8-m resolution), wide fine (8-m resolution with increased swath width) and standard (25-m resolution). The SAR instrument on board the RCM satellites has two additional modes not available on RADARSAT-2: high resolution (5-m resolution) and very high resolution (3-m resolution). RADARSAT data are available through e-GEOS, S.p.A.

TerraSAR-X

TerraSAR-X is a SAR EO satellite, owned and operated in a public–private partnership between the German Aerospace Center (DLR) and EADS Astrium. The satellite's X-band SAR antenna (wavelength 31 mm, frequency 9.6 GHz) acquires high-resolution radar images of the planet from a polar orbit at an altitude of 514 km. TerraSAR-X acquires radar data in the following three main imaging modes: SpotLight (1-m resolution), StripMap (3-m resolution) and ScanSAR (16-m resolution). TerraSAR-X has a revisit time of 11 days at the equator. The revisit time decreases towards the poles and at mid-latitudes (e.g. northern Europe has a revisit time of approximately 3–4 days).

COSMO-SkyMed

COSMO-SkyMed is an Italian EO SAR imaging constellation consisting of four identical satellites launched between 2007 and 2010, all of which remain operational. The mission is funded by the Italian Ministry for Universities and Research and Ministry of Defence and is owned and operated by the Italian Space Agency. COSMO-SkyMed carries a SAR-2000 sensor on all four satellites. The sensor is a multi-mode instrument, a programmable system providing different performance characteristics in terms of swath width, spatial resolution and polarisation configurations. Several modes of operation are possible, including Spotlight (1-m resolution), Stripmap (3-m resolution and ScanSAR Wide (30-m resolution). The highest resolution data collected is released only to the military, with the two lower resolution modes more generally available.

ICEYE

ICEYE is a Finnish SAR micro-satellite manufacturer and operator. ICEYE operates a constellation which currently consists of 16 X-band SAR satellites. The company plans to continue growing its constellation capacity in specialised orbital planes designed to provide persistent monitoring capabilities and high-resolution SAR imagery of the Earth's surface (Figure 1.2). ICEYE uses commercially available off-the-shelf components as much as possible to reduce costs.

The X-band SAR instruments on board the satellites operate in three primary modes: strip mode (3-m resolution), spot mode (1-m resolution) and scan mode (15-m resolution). The constellation provides a revisit time of approximately 5 hours at mid-latitudes (e.g. Ireland).

Capella Space

Capella Space is a US space company developing and operating a constellation of eight very-high-resolution

Figure 1.2. ICEYE strip mode SAR image of Suvarnabhumi International Airport, Bangkok, Thailand, 9 July 2020. Image credit: ICEYE.

SAR satellites. Currently, the Capella Space constellation offers a revisit time of approximately 5–6 hours at mid-latitudes; however, the aim is to lower that to approximately 1 hour by launching more satellites. The satellites are capable of three modes of image acquisition: spot (0.3-m resolution), site (0.5-m resolution) and strip (1.2-m resolution). Unlike ICEYE, Capella Space provides an advanced user backend and application programming interface (API) for ordering, tasking and acquiring imagery. Users can set up automated image tasking and download data via a graphical user interface or API, making the process of acquiring imagery significantly easier than with any other provider.

Summary

Table 1.1 summarises the information on the satellites reviewed in sections 1.1 and 1.2.

1.3 Drones for Earth Observation

1.3.1 Drone formats

A drone or an uncrewed aerial vehicle (UAV), according to the definition given by the International Civil Aviation Organization (ICAO, 2005), is an aircraft operated without a human pilot on board. A drone can be either remotely controlled by an operator on the ground or pre-programmed to fly specific routes.

Drone technology provides enormous benefits and opportunities in a vast range of disciplines. Drones support tasks such as surveying, humanitarian work, disaster risk management and transport (Ayamga *et al*., 2020). In agriculture, for example, drones can provide real-time imagery and sensor data from farm fields that cannot be quickly accessed on foot or by vehicle (Malveaux *et al*., 2014). Global positioning systems (GPSs) and customisable apps

Table 1.1. Information on satellite resolution, cost and data access

Satellite	Operator/ owner	Sensor	Resolution	Max. revisit time	Cost	Data access
Sentinel-1	ESA	SAR	10 m	6 days	Free	https://scihub.copernicus.eu/
Sentinel-2	ESA	Multispectral	10 m	5 days	Free	https://scihub.copernicus.eu/
Landsat 8	NASA/ USGS	Multispectral	15 m, 30 m	16 days	Free	https://earthexplorer.usgs.gov/
Landsat 9	NASA/ USGS	Multispectral	15 m, 30 m	8 days (with Landsat 8)[a]	Free	https://earthexplorer.usgs.gov/
SPOT 6, 7	Airbus Defence	Multispectral	1.5 m, 6 m	1 day	€10–20/km	https://www.skywatch.com/
GeoEye-1	Maxar	Multispectral	0.41–1.65 m	3 days	€10–20/km	https://www.skywatch.com/
WorldView-1	Maxar	Panchromatic	0.5 m	1.7 days	€20–30/km	https://www.skywatch.com/
WorldView-2	Maxar	Multispectral	0.46–1.84 m	1.1 days	€10–30/km	https://www.skywatch.com/
WorldView-3	Maxar	Multispectral	0.31 m, 1.24 m, 3.7 m, 30 m	< 1 day	€10–30/km	https://www.skywatch.com/
SkySat	Planet Labs	Multispectral	0.9–2 m	4–5 days	€10–30/km	https://www.skywatch.com/
Pléiades-1A, 1B	CNES	Multispectral	0.5 m, 0.7 m, 2 m	1 day (12 hours with SPOT)[b]	€20–30/km	https://www.skywatch.com/
RADARSAT	CSA	SAR	3 m, 5 m, 8 m, 25 m	4 days	~€2500 for 8 m	https://www.e-geos.it/en/
TerraSAR-X	DLR and EADS Astrium	SAR	1 m, 3 m, 16 m	2.5–11 days (~4 days in Europe)	~€3000 for 3 m	https://www.e-geos.it/en/
ICEYE	ICEYE	SAR	1 m, 3 m, 15 m	1 day (eventually 12 hours)	~€800 for 3 m	https://www.iceye.com/
Capella Space	Capella Space	SAR	0.3 m, 0.5 m, 1.2 m	1 hour	~€1000 for 1.2 m	https://www.capellaspace.com/

[a]Landsat 8 and Landsat 9 are effectively the same, with the only difference being that Landsat 9 was launched later and has an orbital period offset at 180 degrees from Landsat 8; hence, Landsat 8 and Landsat 9 should be considered one product with an 8-day period.

[b]SPOT and Pléiades are offset at 90 degrees; therefore, although they are slightly different products, they can be used in tandem to get higher frequency coverage of an area.

for smartphones and tablets have provided improved flight durations, reliability, ease of use and the ability to make better use of cameras and other sensors needed for applying drones in a large range of applications (Hogan *et al*., 2017).

Broadly speaking, there are two types of drones: (1) fixed-wing drones, which generate lift as they move forwards, enabling them to sustain velocity through the air; and (2) multirotor drones, which are highly manoeuvrable and can hover and rotate. Each has advantages and disadvantages when it comes to flight range (endurance), battery capacity and payload capacity.

Fixed-wing drones

Fixed-wing drones essentially resemble aeroplanes. Compared with multirotor drones, which are popular for photography and shooting videos, fixed-wing drones are designed to fly faster and cover a larger area. They are also more efficient when it comes to battery use and have longer flight times. For certain jobs, flying just one fixed-wing drone over a site is far more efficient than flying multiple multirotor drones. However, fixed-wing drones cannot hover, and so they require more airspace for long sweeping turns, as well as a runway and/or a launching system for take-off and landing. Additionally, fixed-wing drones are more expensive than multirotor drones and require specialised training, as they are more difficult to operate.

Multirotor drones

A multirotor drone has more than two lift-generating rotors. By changing the speed of the rotors so that the thrust generated is greater than, equal to or less than the forces of gravity and drag acting on the aircraft, the drone can be made to ascend, hover or descend. By varying the speeds of particular rotors, it is also possible to make the drone turn or move in a horizontal direction. Multirotor drones typically have four rotors, although different configurations exist. The more rotors a multirotor drone has, the more thrust it can generate and thus the greater a payload it can lift, but with the trade-off of greater energy requirements (UST, 2022). Drones with more than four rotors also have a degree of redundancy, meaning that they can still make a gradual descent if an individual rotor fails. Larger multirotor drones may have the ability to carry hydrogen fuel cells, which can provide a greater energy output to mass ratio than conventional battery technology.

Multirotor drones, due to their vertical take-off and landing operation, can operate in a much wider variety of environments than fixed-wing drones, as they do not require any extra space to manoeuvre, take off and land (UST, 2022). Their ability to hover in place makes them ideal for surveillance missions and imaging applications. Most multirotor drones, especially smaller ones, are limited to batteries as a power source, which puts limits on their flight endurance. While fuel cells can be fitted to some multirotor drones to improve their flight times, internal combustion engines are too bulky and too unresponsive for their operation, which relies on very fast adjustments to rotor speeds.

1.3.2 Sensors

Drones can be fitted with a wide variety of cameras to capture different kinds of imagery such as HD photos and videos and thermal infrared images, as well as multispectral and hyperspectral images for applications such as precision agriculture. The imaging payload (camera) on the drone may be connected to a control computer that triggers the camera, stores images, records metadata such as camera settings and GPS position, and prepares the image data for transmission. Cameras may also be triggered remotely from the drone’s ground control station.

Thermal cameras

A thermal camera captures and records light in the thermal infrared spectrum, which allows it to record the relative temperatures of various objects within the frame. Each temperature is assigned a colour, allowing the user to see how much heat is radiating from one object in comparison with other objects around it. All objects emit infrared radiation, which is how heat is transferred. Thermal cameras see this radiation and convert it into an image the human eye can comprehend (Figure 1.3). Thermal drones have a large range of uses across many different sectors. They can detect water leaks from differences in the surface temperature of the land depending on the amount of water present. Thermal drones are an effective tool for identifying faults in solar panels and for inspecting power lines. The most significant advantage that they offer is in public safety and security: relief and recovery

Figure 1.3. Thermal infrared image taken from a drone showing a thermal image of a peat fire (left) and a true colour image of the same fire (right). Reproduced from Burke *et al.* (2019); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

operations, fire protection and mobile monitoring are just a few of the applications in which rescuers and security personnel have found drones with thermal cameras to be useful.

Multispectral cameras

Most drone-suitable multispectral sensors can contain between three and five spectral bands and provide far more spectral data than standard HD cameras. However, the interpretation of the imagery requires special training, and the cameras are expensive, costing up to tens of thousands of euro.

Multispectral cameras mounted on drones are used in a variety of industries including the agriculture, energy and construction industries. These sensors can help to collect data related to environmental management such as monitoring plant and tree health, managing crops more effectively using plot-level statistics on plant density, height, vigour, leaf area and canopy cover, or reviewing the health of forestry and vegetation. Detailed insights can be secured from multispectral cameras by applying specialised algorithms such as vegetation indexes (Figure 1.4).

Hyperspectral cameras

Hyperspectral cameras are similar to multispectral cameras in that they collect light in multiple bands; however, while multispectral cameras usually collect light in three to five broad bands, hyperspectral cameras have hundreds of very-narrow-wavelength sensors that overlap to cover the full spectrum of visible light, resulting in hundreds of bands.

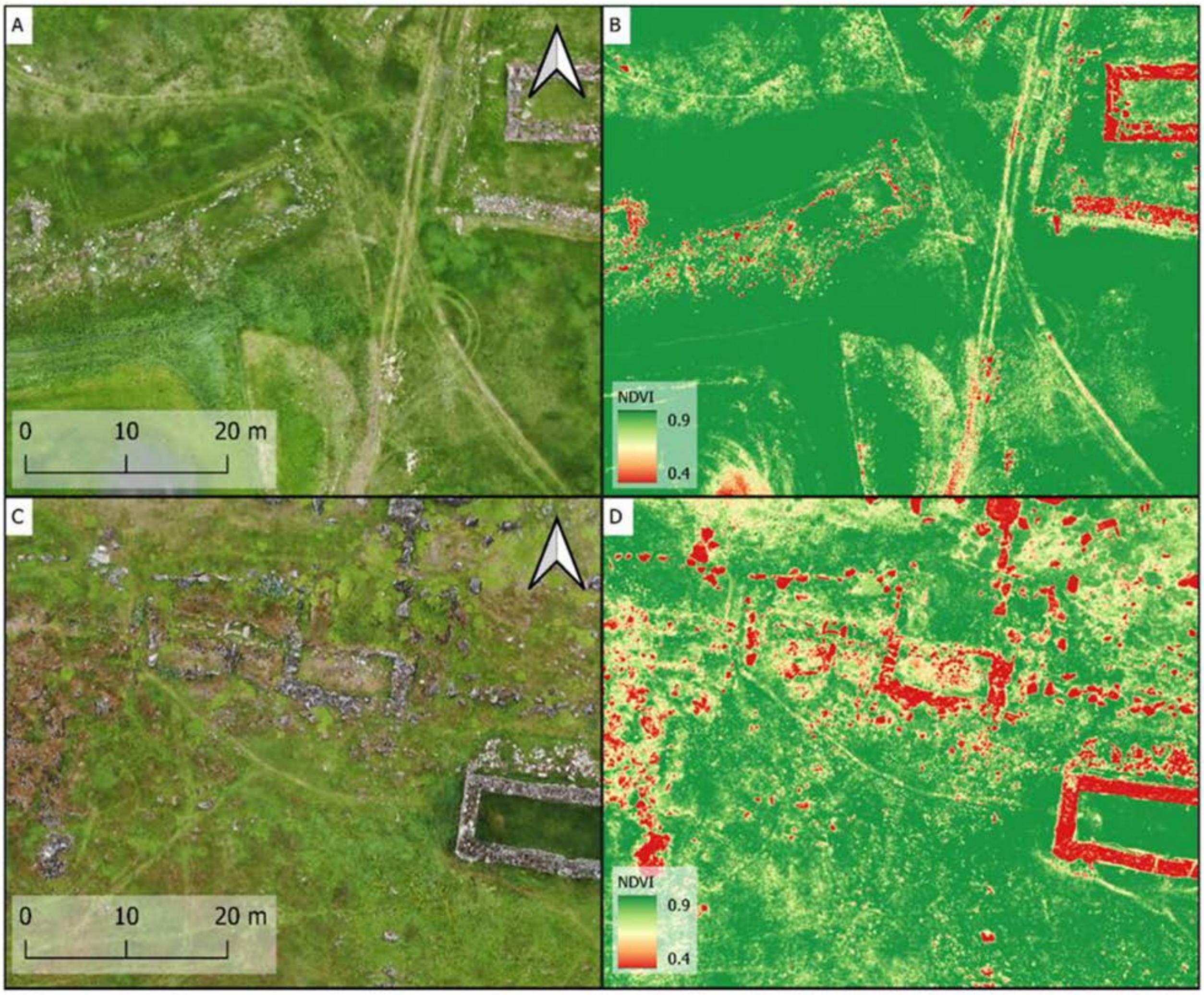

Figure 1.4. True colour (A and C) and NDVI (B and D) images, taken from a DJI drone. NDVI is a measure of vegetation health calculated from the NIR and red spectral bands of a multispectral sensor. Reproduced from Hollesen *et al*. (2023); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Hyperspectral sensors collect data as a series of narrow and contiguous wavelength bands, providing a high level of performance in spectral and radiometric accuracy. Hyperspectral sensors are instrumental in plant health measurement, plant disease identification, water quality assessment, vegetation index calculations, and mineral and surface composition surveys. Hyperspectral sensors provide a better capability to see what cannot be seen with multispectral sensors and in much finer detail.

2 Data Fusion Using Earth Observation

Data fusion refers to the combination of data of multiple types or from multiple sources to create new, richer data. Data may be rich in one aspect but poor in another: for example, multispectral data are spectrally rich, as they contain many different bands recording spectral information at many different wavelengths, but are often spatially poor and have lower resolution than panchromatic data. Panchromatic data, on the other hand, tend to have much higher spatial resolution but contain a single band – a black and white image. However, it is possible to fuse these two data types together to achieve the best of both: spectrally and spatially rich data. EO data may also be fused with non-EO data, such as weather data or data collected by the public, to create a dataset that otherwise could not exist. Remote sensing data are useful in such a wide variety of contexts that novel and seemingly unintuitive data fusion techniques are at the frontier of EO research.

2.1 Image Sharpening

There are many methods of sharpening multispectral images with panchromatic images with varying levels of complexity suited to specific spectral bands, resolutions, and applications; most methods of pan-sharpening aim to limit spectral distortion. The two main approaches, under which most pan-sharpening techniques can be classified, are component substitution and multiresolution analysis. In general, component substitution offers higher resolution but with more spectral distortion, while multiresolution analysis has less distortion but also lower resolution. Some common methods are demonstrated in Figure 2.1.

A primary use of pan-sharpened images is for the purpose of land use/land classification (LULC), where the improved dataset enables more accurate classifications. There are a few ways of classifying land use, with the most common employing machine learning and artificial neural networks (ANNs) and visual classification. An expert can very accurately classify specific land use types, but it is a time- and resource-intensive task to accomplish – particularly in the case of a pan-sharpened image with increased resolution and potentially distracting artefacts. Thus, machine learning and ANN methods are increasingly popular approaches to LULC tasks, as they quickly learn from large training datasets and can then apply the learning to relevant images.

While data captured by a UAV can be of very high spatial resolution, they tend to have low spectral resolution – in contrast to the high spectral resolution and comparatively low spatial resolution of satellite imagery. Therefore, UAV data have been fused with EO data in a manner very similar to pan-sharpening, with the UAV images being used in the same way as panchromatic images (Jenerowicz *et al*., 2017; Zhao *et al*., 2020). Much of the research into the fusion of drone and satellite imagery is on crops, where the multispectral information is crucial in assessing specific aspects of crop health, but the revisit time is too infrequent to be consistently helpful. UAV data are being increasingly used to assist in this regard but may not have the spectral information or ability to cover a large enough area (Sagan *et al*., 2019; Maimaitijiang *et al*., 2020; Zhao *et al*., 2020).

Zhao *et al*. (2020) used UAV and satellite data fusion for vegetation classification purposes. The researchers used the Chinese EO satellite ZY-3, which records multispectral data at a resolution of 2.5–6 m. These data were then fused with optical UAV imagery to create a dataset with improved spectral and spatial resolution (Figure 2.2).

The resulting new dataset was then classified using a variety of supervised machine learning models. Five types of vegetation were classified: trees, maize, peanut, honeysuckle and other. The fused images were more accurate than the unaltered UAV imagery by 5–9%, depending upon the type of machine learning model used. The authors concluded that the value of remote sensing and UAV data fusion in the classification of vegetation is great: the fused dataset improved classification accuracy and the kappa coefficient – a measure of reliability – in each case compared with that of UAV data alone.

2.2 Machine Learning

Machine learning is generally defined as the use of computer systems that learn or adapt without

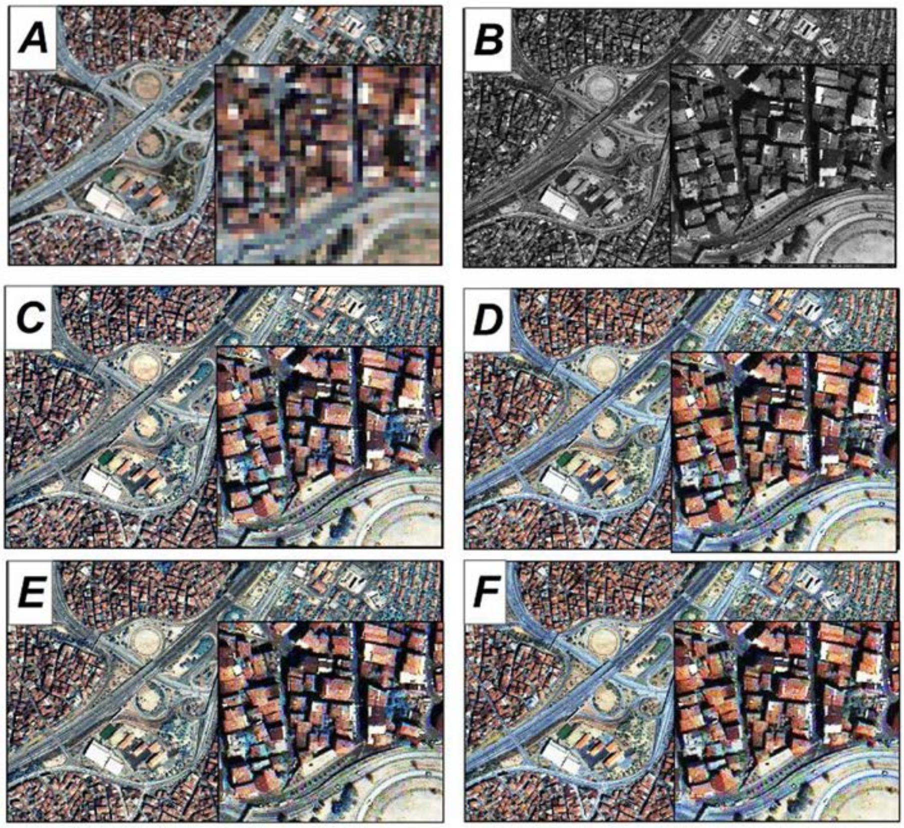

Figure 2.1. Examples of pan-sharpened images. (A) Original multispectral bands of the IKONOS satellite image. (B) Panchromatic band of image. (C) Brovey pan-sharpened image. (D) Gram–Schmidt pan-sharpened image. (E) Intensity–hue–saturation pan-sharpened image. (F) Principal component analysis pan-sharpened image. Reproduced from Sarp (2017); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

requiring explicit instructions. Remote sensing image classification can be accomplished with machine learning models and with neural networks, both with good results. There are many types of machine learning model, each with different advantages. With ANNs, “computer vision” is often used to classify and identify objects in an image. Computer vision is widely used in numerous products, such as facial recognition software, to automatically generate image captions, and it can be used in effectively the same way on remote sensing data. Using machine learning on remote sensing data to classify different types

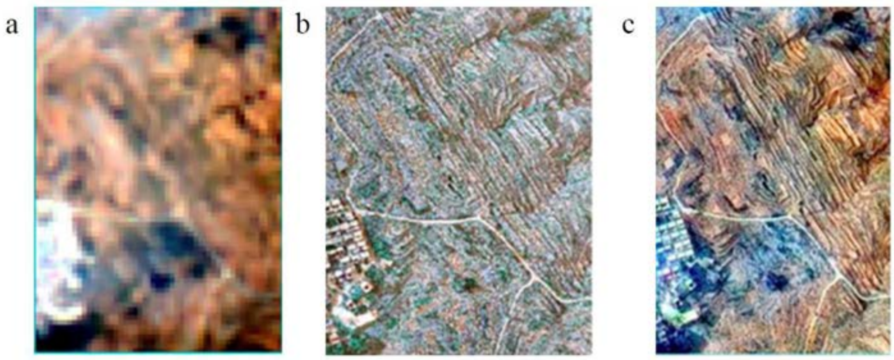

Figure 2.2. (a) True colour multispectral satellite imagery. (b) UAV image. (c) Fused image. Reproduced from Zhao *et al*. (2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

of land use is called LULC. Waste crimes may be considered a type of land use, in that they are land misuse, so detecting waste crime from EO data may be considered an LULC application. In the context of LULC applications, machine learning techniques are generally “supervised”, meaning that there is a training dataset comprising features (either individual pixels or objects – i.e. groups of pixels) and labels (e.g. “agriculture” or “urban”). Each pixel or object in the training dataset has a label so that, when the algorithm has learned the training data, it can look at a previously unseen image and label each pixel appropriately. Supervised machine learning therefore requires a good training dataset: one that has diverse enough classes to cover all desired land uses, is large enough to adequately describe the diversity within each class, and is balanced enough so that biases are not unintentionally introduced into the algorithm.

ANNs, or artificial neural networks, are a form of machine learning based on the structure and function of biological neural networks. The ability of an ANN to learn from relatively unstructured data and to extract important features provides an important opportunity in EO, where myriad aspects such as thick or thin cloud cover or spectral distortion can affect the quality of the data. Neural networks are particularly effective in using the temporal aspect of satellite imagery (Pelletier *et al*., 2019). ANNs have been successfully used for object detection and LULC applications with high success rates. The ability of an ANN to detect the nuanced differences between specific items that appear similar makes the fusion of deep learning and satellite imagery particularly attractive for detecting waste crime.

Neural networks have been used to detect illegal landfills, such as in research by Devesa and Brust (2021). The study adopted a data-driven model from the machine learning domain in order to analyse imagery from Sentinel-2 with a set of known waste dumping sites in Buenos Aires. The locations of other unknown dumping sites were then predicted over vast geographical areas at high speed and low cost.

Devesa and Brust (2021) made use of satellite images from ESA’s Sentinel-2 satellite, with a spatial resolution of 10 m. Two datasets with georeferenced locations of known illegal waste dumps were available: a survey from the Autoridad de Cuenca Matanza Riachuelo (a public agency tasked with improving the environmental quality of the region’s main river basin) and a report from the Buenos Aires Province ombudsman. Together they provided 81 annotations for illegal open air waste dumps, which were used to train a supervised machine learning algorithm.

The study implements a U-Net convolutional neural network (CNN), a class of ANN most commonly applied to analyse visual imagery. The output of the model is an image that is the same size as the input image, in which each pixel is given a probability of belonging to an illegal waste dump. This means that the model finds not only the location of the dumping site but also the boundaries of the site. This feature allows the growth of sites to be measured over time, as well as any potential intersection with other land uses (watercourses, inhabited areas, etc.).

The model uses a set of satellite images with annotations of known sites for the training process. Sentinel-2 images have 13 spectral bands; however, the Devesa and Brust (2021) study used six bands for the purpose of training and running the CNN: red, green, blue, NIR, SWIR-1 and the normalised difference of the two SWIR bands. Previous studies of methane emission detection inspired the use of combined SWIR-1 and SWIR-2 bands, on the assumption that open air waste dumps may emit a significant amount of methane, particularly from organic waste. The researchers (Devesa and Brust, 2021) used NIR and SWIR bands because they are more sensitive for detecting green areas. As large dumping sites are usually located in rural areas, these bands may help to classify the background better. The prediction process produced a set of images with two classes: dumping sites and non-dumping sites. A filter process was applied to all predicted results to remove cases with low probability. Additionally, predicted dumping sites with an area of less than 100 m^2 were removed, as they were likely to be false positives.

The model used by Devesa and Brust (2021) had good ability to predict the location and shape of illegal dumping sites (Figure 2.3). However, the model confused areas of active construction with illegal dumping sites, and any such site with an area of less than 1 ha was difficult to detect due to the spatial resolution of Sentinel-2 imagery (10 m).

Figure 2.3. Results for different locations around Buenos Aires. The red lines indicate the areas predicted by the model to be illegal dumping sites. Reproduced from Devesa and Brust (2021); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

3 Earth Observation in the Irish Context

The major limiting factor for detecting waste crime using EO technology in the Irish context is the weather. Ireland is a country with frequent cloud cover. With average amounts of sunshine ranging from roughly 1.7 days per month in winter to 8.5 days per month in summer, clouds are an omnipresent feature of Irish skies (Met Éireann, 2022). On a cloudy day, multispectral imagery may not be able to get a clear picture of the Earth's surface. Even a partially cloudy day poses problems for most types of analyses: areas beneath clouds lack data, and areas in the shadow of clouds have lower levels of reflectance. This has significant implications for applications such as machine learning, as gaps and shaded areas may lead to unpredictable or low-accuracy results. Many studies will either selectively use cloudless days, mask data from cloudless days into clouded areas or even use deep learning to attempt to recreate what is behind the cloud (Abdi, 2020; Gao *et al*., 2020; Meraner *et al*., 2020) – but, for a service in constant use, none of these is a robust solution. For larger scale waste crime, such as illegal landfills, selectively choosing days when a point of interest can be seen may be enough to assess change. If the affected area is spatially large but temporally brief, such as in some cases of industrial non-compliance, Irish weather is a significant barrier to the use of multispectral imagery.

Because Ireland's cloudy climate inhibits the reliability of multispectral imagery, SAR imagery is more suited to persistent monitoring and dating of short-lasting crimes. SAR's active sensor and ability to pierce clouds make it equally suitable year round. Drones can operate in almost all weather but may be limited by flight time and distance as well as the time of day when a skilled operator is available. Drones are well suited to the Irish context and are very flexible because of the variety of sensors they can accommodate. High-quality commercial SAR products are particularly suited to monitoring waste crime in Ireland, as their efficacy is inhibited by the fewest factors. More case studies on the analysis of various types of waste and environmental crime using EO can be found on the TechWorks Marine website (https://techworks.ie/services/earth-observation/).

3.1 Detecting Wastewater Discharge Using Multispectral and SAR Data

The discharge of untreated wastewater is a significant problem in Ireland, with 32 towns and villages discharging raw sewage into the environment every day in 2021 (EPA, 2022). Illegal sewage discharge by Irish Water due to overflowing systems is common: thousands of incidents have been reported to the EPA, and Irish Water has been prosecuted multiple times in the last few years. For incidents that often occur in cloudy weather, such as those concerning Irish Water, multispectral imagery is not always reliable. Stormwater overflows at the Ringsend wastewater treatment plant (WWTP) in Dublin can discharge into the sea; this problem is more frequent after storms. Following intense rainfall, stormwater overflows mean that occasionally bathing water warnings must be put in place – as happened at the beginning of August 2022 (Griffin, 2022). Although this pollution can be seen using multispectral imagery on a sunny day, the problem is that it often results from rainy – and therefore cloudy – weather.

On 10 July 2018, kayakers on the River Liffey notified the EPA of sewage being discharged into the Liffey. The kayakers described the discharge as comprising reddish-brown foam and particulate matter.[2] In Figure 3.1, the reddish discharge can be seen coming from the Ringsend WWTP and spreading as a dark mass throughout the harbour. The clouds obstruct our vision of the extent of the discharge into the bay, but passengers on a ferry were also able to see the discharge, indicating widespread contamination.

The incident in 2018 is not an isolated one: a similar discharge of sewage occurred in June 2017. In this case, cloud cover interfered with Sentinel-2 coverage of the area, but Sentinel-1 and the commercially available TerraSAR-X images both show discharge

2 This information was provided in a personal communication by Simon Buckley of the EPA, 23 November 2022.

Figure 3.1. Sentinel-2 image showing discharge from Ringsend WWTP on 10 July 2018. A large dark trail can be seen exiting the harbour with a reddish discharge emanating from the WWTP.

into the Liffey in Figure 3.2. The top image, taken by Sentinel-1, shows a large, slightly dark plume, while the higher resolution TerraSAR-X image shows the plume in finer detail. Although the two SAR images in Figure 3.2 are from the same day, they were acquired about 12 hours apart. Since the Sentinel-1 image was acquired in the evening, the spill had had more time to spread across the water surface, perhaps contributing to the increased width of the plume. Despite the different acquisition times, the two images were both acquired at low tide: morning low tide was at 6:03 am and evening low tide at 6:16 pm (Dublin Port Company,

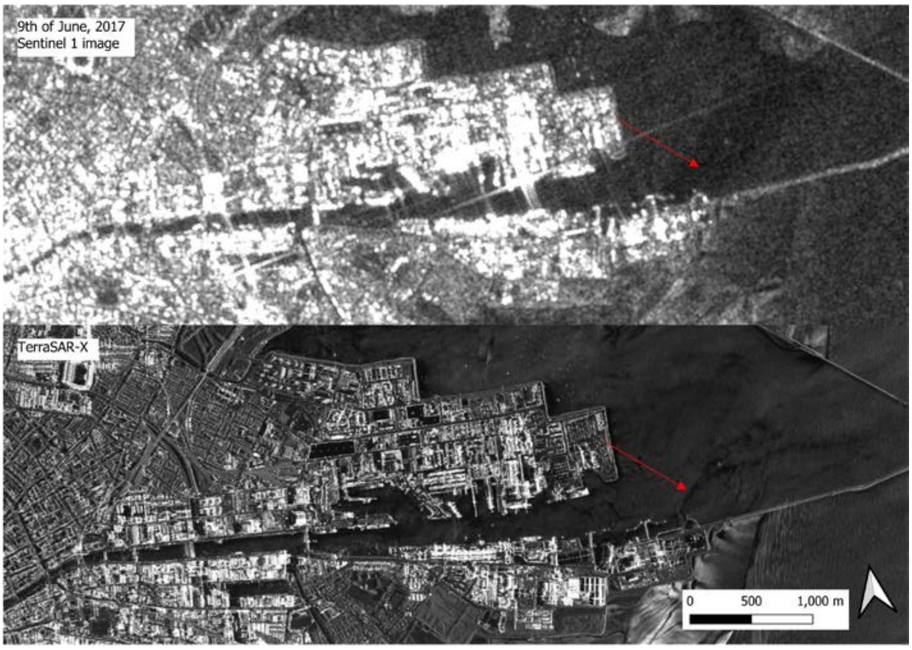

Figure 3.2. Sentinel-1 (top) and TerraSAR-X (bottom) images of a wastewater discharge on 9 June 2017 from Ringsend WWTP. The red arrow indicates the plume of wastewater. The Sentinel-1 image was acquired at 6:14 pm, while the TerraSAR-X image was acquired at 6:51 am.

2017). The low tide may also have contributed to the shape and degree of dispersion of the wastewater plume.

In SAR images, water looks darker than land because it is smoother, reflecting radar waves away from the satellite, which is slightly angled. Different liquids, such as oil, create a smoother surface and reflect the radar waves to a greater extent, appearing darker still than the surrounding water. Sentinel-1's lower resolution image contains artefacts that obscure the image, which are not present in the TerraSAR-X image. The most obvious are what appear to be bright crosses, due to the particularly reflective surfaces of some buildings. While in the Sentinel-1 image these artefacts prevent analysis in tighter city conditions, in the TerraSAR-X image the higher resolution allows analysis of narrow or tight urban environments.

SAR is effective at detecting oil spills because the backscatter qualities of oil differ from those of water, but distinguishing between oil spills and naturally occurring "biogenic slicks" can be difficult (Alpers *et al*., 2017). Optical sensors are usually used to measure proxies for water quality such as turbidity and amounts of coloured dissolved organic matter and chlorophyll-a. The varying optical qualities of a plume can be used to identify the type of pollution involved.

Using data from Sentinel-2, Landsat 8 and the commercially available RapidEye satellites, Ayad *et al*. (2020) analysed and classified stormwater and wastewater run-off off the coast of California. RapidEye was crucial for identifying plumes, while the spectral information from Sentinel-2 and Landsat 8 images was used to assess them. The historical archive of Sentinel-2 and Landsat 8 images was used to create a dataset of 40 images, containing 10 each of stormwater, wastewater, mixed stormwater and wastewater, and a control (i.e. open ocean). The results showed variable spectral qualities of different forms of run-off, with stormwater run-off having the greatest turbidity and containing the most coloured dissolved organic matter (Figure 3.3).

While California and Ireland have very different climatic contexts, the classification of different types of plumes based on their spectral qualities is applicable in Ireland. While SAR imagery is useful for identifying abnormalities – either biogenic or anthropogenic – under most weather conditions (waves can impact the image by introducing noise), optical imagery can provide significantly more information about the type or origin of a plume. The focus on wastewater and stormwater run-off in the research by Ayad *et al*. (2020) is relevant for the Irish context, as this type of

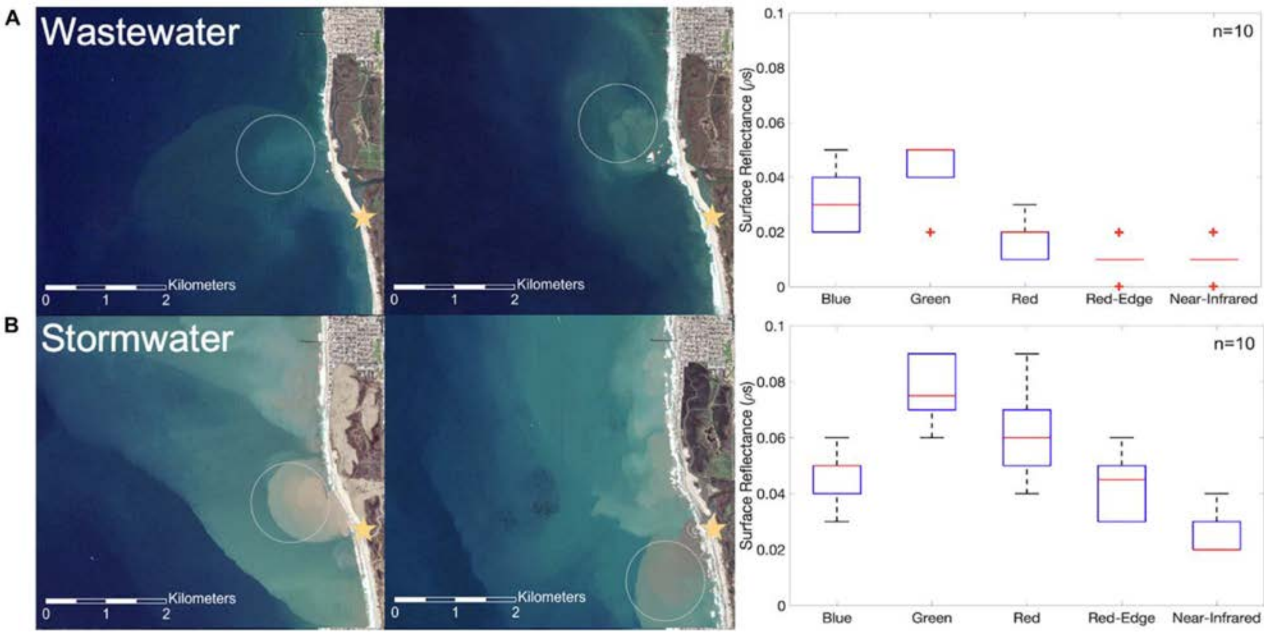

Figure 3.3. RapidEye images of wastewater (top) and stormwater (bottom) plumes and their reflectance values. Stormwater has higher reflectance values than wastewater. Reproduced from Ayad *et al*. (2020); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

surface water discharge is common. Sentinel-2 and Landsat 8 imagery have large enough archives to create a similarly robust dataset of clear days to allow classification in Ireland. The ability to retroactively analyse surface water discharge to gain insights into its composition may be very useful for gathering evidence in cases where the origin of the plume may not be known.

4 Recommendations, Costs and Limitations of Current Methodology

The application of EO technologies for the purpose of gathering information on waste crime falls into two categories: monitoring crimes that have already been reported and detecting crimes that have not been reported. Our recommendations for these two types of evidence collection differ in terms of cost, resource allocation, required expertise level and scope.

In cases where the waste crime or industrial non-compliance is known, EO technologies can be used to monitor changes and document the extent of the crime. Unlike evidence gathered by a drone, the historical catalogue of satellite images lets enforcement authorities look retrospectively at a point of interest before the report was made. Monitoring waste crime with EO technology in this way is therefore reactive and does not detect illegal activity or prevent it from continuing – instead it is a supplementary tool for gathering evidence on the temporal or spatial extent of the crime. Different cases necessitate different levels of expenditure on both personnel and resources, and the use of EO technology will be specific to each case.

Waste crimes vary in terms of severity, temporality and extent, and thus they necessitate different responses. Enforcement agencies may have been made aware of a crime that has already taken place and therefore seek to use remote sensing technology to retroactively gather evidence. Smaller scale or otherwise inconspicuous waste crimes may be such that publicly available data and visual examination provide insufficient evidence that a crime has taken place. In some cases, there may not be a third party to report the crime to an enforcement authority, and thus no action can be taken. To provide viable solutions for a variety of potential waste crimes, multiple levels of service using remote sensing to monitor waste crimes are proposed. Levels 1 and 2 focus on reactive use of remote sensing data, i.e. after the relevant authorities have been made aware of a crime. These two levels are therefore decided on a case-by-case basis. The level 3 service has a national scope and continuing support, and is therefore proactive: its focus is on detecting waste crimes at EPA-licensed sites and notifying the relevant regulatory body.

4.1 Recommendations at Three Service Levels

4.1.1 Level 1 service: monitoring sites with public datasets

The level 1 service would use publicly available EO data such as those from Sentinel-1 and -2. EO technicians would be contracted to work with law enforcement agencies and use publicly available data to examine environmental crime. Due to the resolution of the publicly available products, this type of analysis would be most suitable for waste crime and industrial non-compliance on large spatial scales, such as illegal landfills or unauthorised discharge to surface waters. Change mapping with the medium-resolution EO data that are publicly available is most suited to dating, mapping the extent, and preliminary investigation of waste crime.

This service requires that the regulator be aware of a waste crime. Once a waste crime is reported to the authorities by a citizen or site inspector, the authorities may employ the level 1 service to quickly and cost-effectively check the area and decide if follow-up evidence gathering or action is required.

The low resolution of publicly available satellite images used in the level 1 service may be of limited value as evidence in all but the largest scale environmental crimes. Sentinel missions have high overpass rates but have processing times ranging from 4 hours for Sentinel-2 to 24 hours for Sentinel-1, limiting the viability of these products for timely assessment of ongoing waste crimes. The low resolution and delayed acquisition time make the level 1 analysis of waste crimes most useful as a preliminary or intermediate tool that informs further action. Enforcement authorities may follow up the results of the level 1 service in one of two main ways: by ground inspection or by continuing on to the level 2 service for deeper remote sensing analysis. Ground inspection may always be a required follow-up action, enabling regulatory bodies to gather evidence and escalate enforcement activity accordingly. Personnel may not be able to investigate an environmental crime that is ephemeral in nature, such as wastewater discharge or illegal burning of waste, as the delay in data acquisition may mean that the evidence is gone before authorities can monitor it.

4.1.2 Level 2 service: monitoring sites with commercial datasets

The level 2 service is similar in use to level 1 in that it is used to gather evidence on a waste crime that is already known. Unlike the level 1 service, however, level 2 uses commercially available data, drone data and analytical techniques that require greater expertise.

High-resolution multispectral images can be purchased at a discounted rate from services that sell commercial data for an area of interest by the kilometre, thus avoiding having to purchase the whole image. Multispectral data will have sporadic coverage due to weather conditions, but this affects only the analysis of offences that are ephemeral such as non-compliant wastewater discharge. For other forms of waste crimes, in which waste is static or the crime is repeated frequently, the sub-metre resolution and spectral richness of multispectral data are invaluable for analysing the situation and gathering evidence of financial gain.

Commercially available SAR images from companies such as ICEYE and Capella Space, which cost about €800–€1000 per image, have a revisit frequency of daily or better and 1-m resolution, so they are more valuable and effective than publicly available data. The commercial SAR constellations offer data of greater quality and frequency but may not be available to purchase by the kilometre, unlike multispectral data. Commercial SAR data can used be when exact times and dates are necessary, when the weather is uncooperative or when a specific technique such as interferometric SAR is required.

Drones operate beneath cloud cover and closer to their point of interest, so they can use sensors to collect data that satellites may not be able to, such as optical and thermal data. Although drones can acquire the highest quality data, they require skilled operators, are influenced by weather and have limited flight time, so they may not be as consistent as a satellite making overpasses at exact intervals. Drones are conspicuous, however, and people on the ground may be aware of surveillance and change their behaviour.

As with the level 1 service, this solution will be employed in response to environmental crime that has already been reported. While level 1 may be used mostly as a preliminary check, level 2 will be more suitable for gathering usable evidence. Follow-up action by law enforcement officials may be required.

Enforcement options following the use of commercially available satellite data are, as with the level 1 service, reactive. The main differences in how enforcement authorities may choose to act lie in the quality and timely acquisition of evidence. EO data may be acquired on the same day, potentially enabling authorities to visit a suspected waste crime as it is happening. The better quality of commercially available data makes such data more robust as evidence in cases where the analysis may be used for injunction or prosecution. The ability to retrospectively examine an archive and their high quality make commercial data well suited for small- and large-scale waste crimes.

The presence of enforcement authorities may itself be considered a deterrent: quick responses to waste crime reports are a stronger deterrent than slow responses. In a similar way, the conspicuous sound of drones may modify behaviour locally, also potentially having a deterrent effect. The strategic use of enforcement presence at a known waste crime site may be considered a form of enforcement itself.

4.1.3 Level 3 service: waste crime persistent monitoring and detection using machine learning

The level 3 service represents a nationwide service that uses machine learning to monitor both EPA- and local authority-authorised sites, and functions as a tool to investigate reports. Unlike the previous two services, this is a tool that notifies authorities of anomalous activity in addition to serving as a platform on which data can be easily accessed and reports analysed. The level 3 service focuses more on industrial or agricultural non-compliance than waste crimes with small spatial scales, as industries have the greatest capacity to cause widespread damage to human health and the environment. To prevent large-scale environmental crimes, detecting non-compliance as it happens is crucial. Machine learning models using high-frequency, high-resolution satellite technology will be able to quickly detect deviations from a baseline at the site of each company. When non-compliance crime is detected, follow-up investigations may be conducted by ground personnel or using techniques specifically suited to the suspected illegal activity (e.g. interferometric SAR at a potential peat extraction site).

This service would combine multiple data types and sources to examine changes at different levels and would be both proactive and reactive. The whole of Ireland would be monitored using freely available multispectral and SAR imagery from Sentinel-1, -2 and -3 to create an up-to-date map of the country with each licensed site labelled. As is currently the case with the EPA's mapping website,[3] each labelled location could be clicked on to provide information on the type of site, previous infractions (also available from the EPA[4]), and current and previous licences. The current service available to the public could be used as a foundation for a more robust service designed for enforcement authorities. As for proactive waste crime prevention, the machine learning model interprets the most recent data to detect potential waste crimes throughout the country's licensed sites, creating reports for authorities. When a waste crime is detected, enforcement authorities will be able to easily access the most recent higher resolution commercial multispectral and SAR data to further investigate and potentially validate the report. At problematic sites where frequent non-compliant industrial activity has taken place, commercial satellite data can be tasked at regular intervals to provide consistent training data for the machine learning model.

However, the service can also be used in a reactive fashion, adapting to reports from the public and using citizen science to find waste crimes and improve the machine learning model. Complaints made by the public, paired with GPS data from the site that is the subject of the complaint, prompt the model to analyse the region for a waste crime. The abundance and frequency of complaints inform the model of the likelihood that a waste crime has taken place. If the resolution of the imagery is not enough to analyse the waste crime, authorities can acquire higher quality commercial imagery from within the service. Enforcement authorities can then investigate the temporal extent of the crime as it happens. As with licensed sites, the results of analyses stemming from reports can be fed back into the machine learning model to improve its efficacy.

Because of the relatively high frequency of public satellite data and the use of supplemental commercial imagery, a large repertoire of images of specific sites would be collected, creating a more robust model. With many bands in multispectral data and additional layers provided by SAR data, different types of waste crimes would be identified in different ways by the model. In both correct and incorrect detections, the result would be fed back into the machine learning model to improve its future functionality: there is therefore always an opportunity to improve the model.

The level 3 service functions at a national level, in contrast to the previous solutions, which are used on a case-by-case basis and are therefore more localised. This service would include the ability to monitor known locations on a national scale as well as to focus on a specific location as per the needs of local authorities on a case-by-case basis. Similarly, unlike previous solutions, which are paid for case by case, this solution would be a paid-for service. Purchasing commercial imagery for deeper analysis may incur costs in addition to running the service. Commercial multispectral imagery can be acquired for only a desired subset of a larger area and would cost around €30/km. SAR imagery currently cannot be acquired in this way, and each full image costs between €800 and €2000.

As a service with continuing support, level 3 would offer the greatest flexibility with regard to enforcement of regulations. Because level 3 analyses the most recent EO data on a continuous basis, it would afford enforcement agencies the most time to take follow-up action such as sending personnel. The on-the-fly classification model would be able to quickly detect potential waste crimes that might not otherwise be reported. Furthermore, because level 3 provides the same access to commercial data analysis as in the

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3 https://gis.epa.ie/EPAMaps/ (accessed 6 June 2023).

4 https://www.epa.ie/our-services/compliance--enforcement/whats-happening/national-priority-sites-list/ (accessed 6 June 2023).

level 2 service, it has same capability as the latter as an evidence-gathering tool.

As a form of persistent monitoring, the level 3 service is itself an enforcement tool, because it detects and documents changes over time and frees enforcement authorities from relying only on outside reports or site visits by personnel.

4.2 Budgetary Estimates for Such Services

Any EO data service, irrespective of the level of service as described above, has a set-up cost to put it in place and then running costs. We have provided some indicative estimates of the costs of the three service levels, which reflect the costs of the different resolution data, in Table 4.1. We would recommend that, for prevention of environmental crime to be successful, a level 3 service would need to be established through which the EPA and local authorities would be able to proactively manage waste crime and track the regulation of authorised sites as well as new waste crimes. We believe that machine learning will be an important tool to assist with the proactive identification of such crimes.

4.3 Gaps and Limitations in Current Methodology

As EO technology becomes more ubiquitous and commercial satellites with high resolution and short revisit times become more common, higher quality data will become more affordable, and the obstacles to using EO to detect and monitor waste crime will be reduced.

The techniques involved in processing EO data are also improving, and novel ways to use the same data could create new opportunities for analysis using current constellations. SAR data are exceptionally rich but simultaneously difficult to process because of the way that radio waves reflect and scatter. Although, in the case of surface-level analysis, the phase and different backscatter patterns of SAR imagery often result in noisy images, the information held in these data can be extracted and used for novel analyses, for example using natural seismic movements to enable exploration of the internal structure of a point of interest (Catapano *et al*., 2022). The number of SAR data is an obstacle to using them efficiently, so there is a need for more efficient methods for interpreting the raw data and for greater storage capacities (Rodger *et al*., 2023).

Detecting gaseous pollutants is currently possible to some extent with satellites such as Sentinel-5P, a precursor mission to Sentinel-5 that measures air quality. Sentinel-5P records information about aerosols, ozone, sulphur dioxide, nitrogen dioxide, carbon monoxide, formaldehyde and methane. The satellite has low resolution and is not well suited to the waste crime context, but may have other contextual uses. The launch of Sentinel-4 and -5, which are also designed for monitoring air quality and atmospheric composition, may make assessing illegal aerosol production and identifying air pollution from non-compliant industries viable. As more missions are launched and existing constellations gain more satellites, the quality and frequency of EO data will increase.

EO methodologies are not suited to analysing some types of offences. Trafficking of waste is a large component of waste crime, but EO satellite technology is not capable of monitoring this activity. The spatial and temporal resolution of EO data are too low to follow vehicles, so they cannot be tracked in the same way as ships. Additionally, non-compliant activities may take place indoors, so the effects of the activities may not be visible without a site inspection.

Table 4.1. Estimated costs of each service level

	Cost (estimate) €000s		
Service level	Service establishment and set-up	Monthly service provision	Additional third-party data budgets
Level 1	100–150	6–10	Publicly available data used
Level 2	100–200	6–12	0–400
Level 3	250–350 (includes machine learning development and training)	10–16	0–400

5 Conclusions

Waste crimes, industrial non-compliance and environmental crimes are costly to clean up, so detecting and preventing them early is of economic benefit. Detecting these types of crimes requires significant personnel and other resources, but improved methods for detecting and monitoring waste crimes can make current practices more effective and efficient. EO technology is quickly becoming ubiquitous as new techniques are developed to harness the increasing number of satellites equipped with state-of-the-art instruments. Public and commercial satellite constellations are improving and are equipped to record more detailed data more frequently. Drone technology, which is already employed by enforcement authorities in Ireland, is also an invaluable tool for monitoring waste crime. Drones and satellite constellations have different use cases but can also be used synergistically.

Different data sources can be fused together to create more robust datasets, allowing new and innovative analyses. Alongside improvements in satellite hardware are developments in the machine learning models and processing tools to allow quick, highly accurate classification of images. In the context of waste crimes and industrial non-compliance, high spatial and spectral resolution imagery can reveal an offence in great detail, but it is the catalogue of images that makes EO data particularly valuable, as it enables enforcement authorities to investigate activity retrospectively in response to a report.

Three recommendations for services are made, tailored to the various needs that enforcement authorities may have. Using public and commercial data as well as machine learning tools and citizen engagement, these services are suited to detecting various types of environmental crime throughout the country. While the first two levels of service are reactive – they rely on reports by the public – the third level of service is also proactive and aims to detect offences using a machine learning model based on known environmental crimes and user reports. Although EO technology alone is not a solution for environmental crimes, it has the ability to detect offences earlier and improve the efficiency of enforcement authorities' current practices.

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Abbreviations

ANN	Artificial neural network
CAVIS	Clouds, aerosols, vapours, ice and snow
CNES	Centre national d’études spatiales
CNN	Convolutional neural network
EO	Earth observation
EPA	Environmental Protection Agency
ESA	European Space Agency
GPS	Global positioning system
H	Horizontal
HD	High definition
LULC	Land use/land classification
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NIR	Near infrared
NOAA	National Oceanic and Atmospheric Administration
RCM	RADARSAT constellation mission
SAR	Synthetic aperture radar
SWIR	Short-wave infrared
UAV	Uncrewed aerial vehicle
USGS	United States Geological Survey
V	Vertical
WWTP	Wastewater treatment plant

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

> Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
> Sceitheadh fuíolluisce uirbigh;
> Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
> Foinsí radaíochta ianúcháin;
> Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

> Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
> Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
> Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
> Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
> Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
> Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
> An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

> Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
> Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
> An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
> Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

> Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
> Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

> Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
> Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
> Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

> Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
> Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
> Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
> Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
> Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

> Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
> Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

> Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
> Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
> Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
> Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

> Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
> An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
> Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
> Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

> Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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