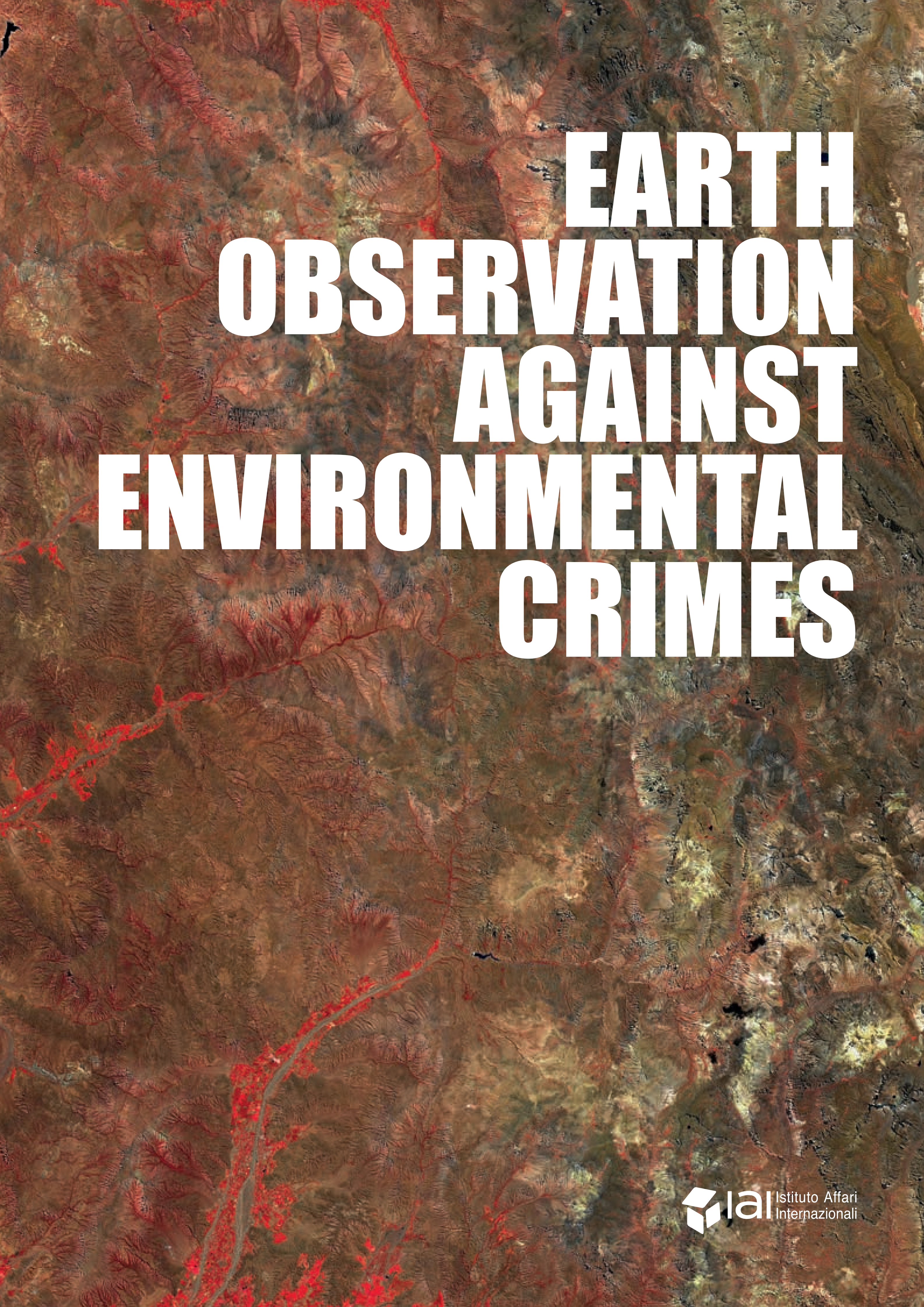

EARTH OBSERVATION AGAINST ENVIRONMENTAL CRIMES

Istituto Affari Internazionali

EARTH OBSERVATION AGAINST ENVIRONMENTAL CRIMES

A REVIEW OF USERS AND USAGES WORLDWIDE

Istituto Affari Internazionali

The Kakhovka reservoir in Ukraine, after the destruction during the Russian occupation of the area. Contains modified Copernicus Sentinel data (2024), processed by ESA.

Contents

Lithium extraction in the Atacama desert in Chile. Contains modified Copernicus Sentinel data (2026), processed by ESA.

About this report

Earth Observations against environmental crimes is a project led by the Rome-based Istituto Affari Internazionali (IAI), one of the leading European think tanks, under an assignment from the European Space Agency (ESA). The project aims at delivering the first-ever comprehensive analysis on the use of satellite images to counteract environmental crimes at the global level, with a specific focus on the data supplied by the EU's Copernicus programme and its Sentinel satellites. In this sense, the research does not focus on environmental monitoring as such, rather on applications that can also contribute to the enforcement of environmental regulations and the liability of environmental offenders. The project aims to identify the current uses and users of satellite Earth Observation (EO) in the fight against environmental crimes, as well as the benefits of employing such applications. It also aims at understanding the main elements favouring the uptake of satellite EO, as well as the obstacles from a technical, political, operative, judicial and legislative point of view. The analysis focuses then on the employment of EO data against environmental crimes, the readiness of legislative and operative frameworks, the awareness of players involved in counteraction on the employment of satellite data, and on the measures and tools to facilitate their use in investigations, their acceptance in court and their inclusion in old and new legislation, among other aspects. This report also gathers case studies of successful applications from key sectors.

The Istituto Affari Internazionali seeks to promote awareness of international politics and contribute to the advancement of European integration and multilateral cooperation. IAI is part of a vast international network, and interacts with the government and its ministries, European and international institutions, universities, major national economic actors, the media and the most authoritative international think tanks. IAI works on sustainability, climate change and the energy transition mainly through research, training and dissemination activities. The *Energy, Climate and Resources* programme of the Institute works extensively on many dimensions of the energy markets, policies and geopolitics of the European Union and their implications in the Euro-Mediterranean region. IAI has also significant experience with environmental crimes, environmental monitoring and the use of satellite imagery analysis. These topics have been addressed by a variety of projects with environmental and law enforcement agencies from the EU, Sub-Saharan Africa, Southeast Asia and Latin America, such as **Ambitus** and **Unite**.

READING GUIDE

SAR image of the Singapore Strait, showing vessels in the area. Contains modified Copernicus Sentinel data (2026), processed by ESA.

This report aims at providing useful, ready-to-use information designed for all players involved in action against environmental crimes – enforcement agents, prosecutors, judges, representatives of civil society, members of academia and representatives of international organisations. It has the twofold objective of giving fundamental information about how EO is and can be used against environmental crimes, including how its use can be empowered; and of sharing practical data about successful applications, key players and availability of data and platforms.

A set of definitions is provided in the Glossary at the end of the report. The structure of the analysis is divided as follows:

GENERAL ANALYSIS

This part contains essential information about how and why EO is being used around the world to fight environmental crimes. In particular:

Fundamentals
Provides some background information about new trends in environmental crimes and on how EO data can support the fight against them.

EO and environmental crime legislation
This part specifically reviews the interaction between national, international and European legislation and EO applications. It focuses on international treaties, EU laws and national legislation (considering the general approach of most countries, and specific national cases).

Landscaping the use of EO
Provides an overview about the findings from our analysis, describing in particular how satellite data are actually being employed by different categories of users around the world and identifying the associated benefits and limitations.

SECTORAL ANALYSIS

This part provides insights for each of the main sectors of environmental crimes where EO is applied. Each section provides an overview of applications, and then focuses on users, advantages and obstacles.
It is divided into two sections:

Main sectors
Focusing on areas where applications are more consolidated (forestry crime, illegal pollution, fishery crime and illegal mining).

Other sectors
Discussing areas where applications are promising but use is still limited (sand mining, waste trafficking, illegal construction and wildlife crime).

CASE STUDY ANALYSIS

This part contains ten case studies chosen among the most successful, impactful and replicable applications. In particular:

Satellite detection of illegal logging and water theft in western Mexico
- Topic: deforestation, illegal water abstraction
- Implementing partner: Guardian Forestal *(NGO)*

Remote monitoring of rare earth mining expansion in northern Myanmar
- Topic: pollution, illegal mining
- Implementing partner: Guillaume de Langre *(independent consultant)*

Investigations on palm-oil driven wildfires in Indonesia
- Topic: deforestation, forest fires
- Implementing partner: Bambang Saharjo, University of Bogor *(academia)*

Remote Sensing–Based Enforcement of Environmental Policies in Flanders
- Topic: landscape change
- Implementing partner: Vito Remote Sensing *(research centre)*

Illegal mining investigation in Bangka Belitung
- Topic: illegal mining, pollution, destruction of landscape
- Implementing partner: Bambang Saharjo, University of Bogor *(academia)*

EO to detect and intercept fishery crime
- Topic: fishery crime
- Implementing partner: EFCA *(international organisation)*

Detection of illegal mining in India: Mining Surveillance System (MMS)

- Topic: illegal mining
- Implementing partner: BISAG *(national institute)*

Reducing human-wildlife conflict and poaching in Sub Saharan Africa

- Topic: wildlife crime
- Implementing partner: Eolas *(private company)*

AI (artificial intelligence) detection of illegal landfills and solid waste in Northern Italy

- Topic: illegal waste disposal, waste trafficking
- Implementing partner: POLIMI *(academia)*

Using OSINT and EO to identify recent illegal activities in northern Peru

- Topic: deforestation, illegal mining
- Implementing partner: UNODC *(international organisation)*

METHODOLOGY

This report has been produced through desk research, interviews and a number of missions in the field.

Interviews

The research has engaged a variety of users and players in more than 38 interviews: law enforcement agencies, prosecutors, judges, representatives from civil society, as well as staff from international organisations, and policymakers. A full list of the interviews is available in the Reference section.

Missions on the field

Missions took place in the following countries: Indonesia, Vietnam, Thailand, India, South Africa, Brazil, Chile, Mexico, Costa Rica, the Netherlands and France. The missions were used to collect information about the general use of EO in the country, and about specific applications (a selection of which have been included among the case studies in this report). Missions were conducted both in the central offices of organisations, as well as through extensive work on the ground with local NGOs and volunteers.

All pictures in this report have been taken by the authors during these missions (excluding those included in the case studies, which have been provided by the interviewees).

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The opinions expressed in this publication are those of the authors. The content of this publication is based on the information available at the time of the research, on authors' analysis, and on the information provided by national and international partners involved in the research during the project.

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Expert Group

The results of this report have been discussed in a series of workshops in January and February 2026, involving experts from enforcement agencies, NGOs, academia, international organisations, and other entities, representing a global audience of more than 20 countries.
The report has been then evaluated by a group of experts, which provided crucial feedback before the finalisation of the document.
A special thanks for their effort and for sharing their invaluable expertise goes to representatives from the European Commission, Directorate-General for the Environment and Directorate General for Justice and Consumers, to the European Space Agency, to representatives from Eurojust, to Coen Bussink (UNODC), Luca Maiotti and Andreas Aponte (OECD), Marcena Hunter (GI-TOC/ECOSOLVE), Ruth Nogeron (World Nature Watch), Sven Vrielynck (Natuur and Bos), Bambang Saharjo (University of Bogor), Susana Couto (Department of Investigation and Criminal Prosecution, Azores, Portugal), and Danijela Sinđelić (Chief Public Prosecutor, Obrenovac, Serbia).

EXECUTIVE SUMMARY

Agricultural landscape in the Flandres, Belgium. Contains modified Copernicus Sentinel data (2026), processed by ESA.

THE WORLD IS FACING A NEW, MAJOR WAVE OF ENVIRONMENTAL CRIMES (SEE SECTION FUNDAMENTALS OF SATELLITE EO – INTRODUCTION TO ENVIRONMENTAL CRIMES).

A NEW WAVE OF ENVIRONMENTAL CRIMES

This is the evaluation of most EU and global enforcement agencies, international organisations, NGOs and other players in the sector (Colantoni et al. 2022a), and it is a trend that affects all sectors and all countries – although with some differences. There are indeed sectors that have witnessed a remarkable acceleration in the impact of environmental crimes in the past decade (illegal mining, waste trafficking), and others that have seen mostly an evolution of methodologies, or goods or species being trafficked (wildlife crime, deforestation). This trend is due to several factors, affecting each sector in a different way: the increase in costs of environmental compliance has pushed for the illegal disposal of waste, for instance, while the quickly growing demand for critical minerals and gold due to the digital and energy transition, as well as geopolitical instability, is influencing illegal mining worldwide. The greater rarity (and thus value) of fauna and flora species because of the biodiversity crisis increases earnings for poachers and traffickers, while fines and punishments remain significantly low for most countries and sectors, particularly compared to the high earnings environmental crimes offer. While this has triggered an expansion of the role of organised crime groups (OCGs), there is also a greater importance of white-collar crime, i.e., legal businesses profiting significantly from illegal activities. Criminal methodologies are also evolving and often exploit the slow reaction time of institutions and agencies, complications in cooperation among different countries on transnational crimes, and the often convoluted discovery of environmental crimes.

HOWEVER, A POWERFUL SET OF TECHNOLOGICAL, ECONOMIC, SOCIAL AND POLICY TOOLS TO SUCCESSFULLY COUNTERACT THIS WAVE IS FINALLY AVAILABLE (MAIN TRENDS IN ENVIRONMENTAL CRIMES).

A NEW SET OF TOOLS

This is shown for instance by the increasing political attention to the issue, as the EU has included for the third consecutive time environmental crimes as a priority in its European Multidisciplinary Platform Against Criminal Threats (EMPACT), the leading European platform for cross-cutting coordination against crimes. However, environmental crimes have been central to the activities of several other international organisations, such as UN agencies like the United Nations Office on Drugs and Crime (UNODC), the United Nations Interregional Crime and Justice Research Institute (UNICRI) and the United Nations Environment Programme (UNEP), and of new initiatives such as Eco-Solve, a Global Initiative Against Transnational Crime (GI-TOC) programme focused on addressing the data deficiency issue. New legislation has been enacted, such as the new Environmental Crime Directive of the EU, and there is renewed attention also to the economic and social components of environmental crimes (illustrated by the focus on the whole agriculture supply chain in the ambitious new and twice-postponed EU Deforestation-Free Regulation, the EUDR). Above all, technological tools are among the most promising instruments, and Earth Observation (EO) is one of the most crucial elements: even basic (and relatively cheap) commercial drones significantly cut the time and resources needed for scanning a territory, while networked sensors offer a chance to monitor remotely even distant or inaccessible areas. Satellite data however offer the most flexible, complete and easily available set of tools.

SATELLITE DATA INDEED HAVE NEVER BEEN SO ACCESSIBLE AS THEY ARE NOW, AND APPLICATIONS HAVE NEVER BEEN AS EFFICIENT IN COUNTERACTING ENVIRONMENTAL CRIMES (INTRODUCTION TO THE USE OF SATELLITE EO IN THE FIGHT AGAINST ENVIRONMENTAL CRIMES).

AVAILABILITY OF DATA

Satellites have been employed in fighting environmental crimes at least since the 1980s-90s, but in the past this was done mostly in relation to specific occasions and with significant limitations (largely focused on environmental emergencies, such as breaches of dams containing mine tailings). While the efficiency of satellite-based systems like the Brazilian DETER (Sistema de Detecção de Desmatamento em Tempo Real) showed the potential of such tools to counteract issues such as deforestation, the launch of new missions by a number of governmental space agencies significantly boosted the availability of data. This has massively further expanded since 2014 with the European Copernicus programme and its Sentinel missions. As a consequence, players in the fight against environmental crime now have access to a unprecedented amount of free data accessible through a series of public “distribution platforms”, and even

GEOGRAPHICAL COVERAGE

paid images have seen a significant decrease in cost in the past few years (Interviews 32 and 35). Data are more available now in terms of geographical coverage (as the Sentinels cover almost the totality of the globe) and revisit time (each location being scanned every five to ten days by the Sentinels), and in terms of the kinds of data. Indeed, not only optical data are now freely available, but also a variety of multispectral data (see **Table 1**). As multispectral images can see what is normally hidden to the human eye, and Synthetic Aperture Radar (SAR) images even ignore the cloud cover blocking traditional optical satellite images, these advantages have significantly expanded the employment of EO. This renewed availability concerns not just the raw data, but also the processing tools required to transform raw EO data into actionable information. Several players are indeed delivering new applications able to expand the detection of offenses (spotting illegal mines covered by the forest canopy, or detecting dark vessels committing fishery crime, for instance), or to automate the scanning of territory and the discovery of suspicious activities (a selection of the most relevant global cases is discussed in the **Case studies** section of this report).

ROLE OF AI

AI is playing a significant role in the automation of applications, and is proving particularly effective in scanning large territories or in advanced detection techniques (such as those applied to spotting dark vessels). In this sense, several players are now developing "thematic platforms" that integrate satellite data, as well some of these tools, usually with a thematic or geographic focus. The main difference between thematic and distribution platforms is that the first provide information which is ready-to-use for the fight against environmental crime, whereas the second distribute more general data (as in the case of Copernicus Browser). For example, Global Nature Watch (formerly Global Forest Watch) presents to the users EO-derived vegetation disturbance monitoring data along with some contextual geospatial information, which can then be used to assess and determine the legality or illegality of the clearing, which could be related to illegal logging, illegal gold mining, or illegal land use change. It incorporates the RADD (Radar Alerts for Detecting Deforestation) forest disturbance system, based on Sentinel-1 data and used to detect early signs of deforestation and act pre-emptively. The Global Fishing Watch Map offers a global, publicly available detection of dark vessels (focusing on fishery crime) while the Guardian Forestal works instead on both forestry crime and illegal water abstraction, but only for four Mexican states. The expansion of the Sentinel missions in the next years will also further expand the available data and will further contribute to usage (**Increasing data availability: The Copernicus Sentinel Expansion missions**).

THIS NEW ENDOWMENT OF DATA OFFERS SIGNIFICANT ADVANTAGES (MAIN BENEFITS)

ADVANTAGES OF USING EO

Broadly speaking, EO has two main benefits: it saves time and resources on activities that are already carried out through alternative methods, and it performs tasks that would be otherwise impossible. For instance, scanning the territory for illegal waste disposal through EO is much more successful and costs a fraction of traditional on-the-ground monitoring by officers (**Case 9**). Similarly, the identification of illegal water abstraction through interferometry (**Case 1**) allows for the detection of water theft in private properties that would otherwise be particularly complicated through traditional individual inspections. Additionally, using EO allows remote monitoring of suspicious locations, reducing both the number of officers employed, and their exposure to safety and health risks. Officers can understand in advance whether the site they are visiting for an illegal waste disposal case has hazardous waste and take precautions (**Case 9**). Areas where the involvement of OCGs threatens the safety of officers can be monitored at a distance; this is for instance the case for illegal mining in the Amazon (**Case 10**) or water theft for avocado cultivation in Mexico (**Case 1**). EO permits also to investigate cases in areas that are inaccessible due to political instability or even conflicts, for example illegal mining for critical minerals in Myanmar (**Case 2**). While systems such as the abovementioned RADD allow also the prevention of environmental crimes, such applications have also had in some cases a deterrence effect: EO monitoring of the territory of Flanders to detect illegal landscape changes has significantly decreased the number of environmental violations (**Case 4**). The automation of processes through AI and public platforms also significantly reduces the need for specialisation by enforcement agencies and other users, a chronic issue in action against environmental crimes (**Obstacles – Operative obstacles**).

DESPITE ALL THESE ADVANCEMENTS, THERE STILL EXIST RELEVANT LIMITATIONS TO THE USE OF EO AGAINST ENVIRONMENTAL CRIMES.

MAIN LIMITATIONS OF APPLYING EO

Technical limitations still have an impact (**Main obstacles – Technical obstacles**); in some cases, and particularly for some kinds of offenses (see **Wildlife Crime** for instance), Very high resolution (VHR) images are required,

OPERATIVE, LEGISLATIVE, JUDICIAL OBSTACLES

which are not freely available in most cases and need to be purchased. While the Copernicus programme has offered a complete database since the end of 2016, VHR data and data from private providers have a very limited availability for past instances, but will instead be much more useful for future investigations. Private providers are also in several cases not accustomed to working on environmental issues, having instead a significant focus on security topics; players in the sector have thus in some cases faced difficulties in having their specific requests for data satisfied (Interview 31). Geographical factors can also influence the use and effectiveness of EO data. In tropical regions, for instance, persistent cloud cover limits the use of optical data. In such contexts, SAR data can still be used as SAR is not affected by atmospheric conditions; however, it provides different types of information than optical data and is typically less readily available (**Main factors influencing applications**). While the use of satellite EO data does not eliminate the need for ground investigations and complementary data collection, it can significantly reduce their burden; officers will, for instance, be able to focus only on a smaller number of the most suspicious sites, rather than investigating all potential locations. Above all, main obstacles relate to organisational issues (**Main obstacles – Operative obstacles**), lack of policies (**Main obstacles – Legislative obstacles**) and poor awareness (**Main obstacles – Operative obstacles and Judicial obstacles**). Indeed, in most cases enforcement agencies and other players involved in action against environmental crimes neither systematically include EO usage in their work, nor they have adequate capacity building to create expertise inside the organisation. Also on the national or international level most environmental policies and treaties dedicate little to no attention to the uses of EO data (**EO and environmental crime legislation**); while the EU has started to incorporate the use of Copernicus in its Green Deal legislation, there are still some instances where this is missing, most notably in its new 2024 Environmental Crime Directive (**EO and environmental crime legislation – EU legislation**). Above all, most organisations have insufficient awareness of the possibilities offered by EO, and often believe these are much less effective and available, and much more expensive than is actually the case. While this is a common occurrence among enforcement agencies, and less so for civil society, it is particularly valid for judges and prosecutors, who have shown the lowest adoption and awareness on EO applications against environmental crimes among all players in the sector (**Main Obstacles – Judicial obstacles**). In some countries, the use of satellite imagery requires a certification process in order to be admissible in court (**EO and environmental crime legislation – Certification of satellite data**). While this process has been effectively systematised in countries such as the US, Brazil, or Peru, in others it remains yet to be regulated and is instead left to the discretion of individual judges

LEGISLATIVE FRAMEWORKS PLAY A SIGNIFICANT ROLE IN EMPOWERING OR UNDERMINING THE USAGE OF EO AGAINST ENVIRONMENTAL CRIMES (EO AND ENVIRONMENTAL CRIME LEGISLATION – LEGAL SYSTEMS).

ROLE OF LEGISLATIVE FRAMEWORKS

Satellite data are employed equally in criminal and administrative law, but they are usually more common and more efficient for cases involving the latter. This is due to a variety of factors; administrative proceedings are usually quicker and require a lesser burden of proof than criminal law, and are more effective towards environmental crimes (mostly because such offenses are largely economic crimes, and fines when adequate have a significant impact on perpetrating organisations). However, national systems usually mix the two approaches, and some countries favour one over the other, with various impacts on the use of EO in court: a country favouring the use of administrative law for environmental cases (such as Sweden or Belgium) would generally use satellite data more easily than those focusing on criminal law (as in the case of Spain).

THIS RESEARCH HAS IDENTIFIED THE MOST COMMON FEATURES AND METHODS OF APPLICATION OF EO AGAINST ENVIRONMENTAL CRIMES, STEMMING FROM THESE ADVANTAGES AND LIMITATIONS (LANDSCAPING THE USE OF EO AGAINST ENVIRONMENTAL CRIMES).

Three findings are particularly relevant:

- **Satellite applications are more widely employed for monitoring than for prosecution and judgments.** In other words, it is much more common to see civil society and enforcement agencies using satellite data to detect anomalies and trigger investigations, than to find court cases where prosecutors have employed them as evidence. In some cases, this is simply due to timing – environmental cases could last more than a decade, and the mainstream use of EO in the sector has greatly expanded in the past ten years. While it is also generally true that environmental cases do not reach courts as much as other kinds of offenses (Colantoni et al. 2022a), also the low awareness of the judiciary towards these tools plays a significant role. Finally, in some cases EO applications do not reach courts because they are used to start investigations (for instance, for the early detection of illegal mines or suspicious fishing activities). As work on the ground usually follows these first stages of investigation, it then generates traditional evidence to be used in court.

- **There is also a strong difference between targeted applications, and uses involving general and thematic platforms.** In the first case, data are collected and then investigated over a specific occurrence, usually involving an advanced level of analysis. In the second case, enforcement agencies or other actors use platforms providing already processed information, as in the case of Global Nature Watch. Targeted applications are less frequent, as they require greater resources, expertise and awareness, but they also offer much more flexibility and accuracy, and are much more likely to result in a successful investigation. The second category of applications is instead much better suited for general monitoring, or for the preliminary stages of investigations. In this sense, these two occurrences can be complementary: enforcement agencies could do a general scan of locations where they suspect environmental crimes are taking place using general or thematic platforms and involving non-expert users, and then move to more detailed and complicated EO-based investigations if needed.

FINALLY, WHILE MANY IN THE ENVIRONMENTAL ACTION COMMUNITY STILL CONSIDER EO A STAND-ALONE TOOL, INTEGRATION WITH OTHER TECHNOLOGIES, AMONG DIFFERENT SATELLITE DATA AND WITH OTHER INVESTIGATIVE TOOLS IS CRUCIAL.

NEED FOR COMBINING EO WITH OTHER TOOLS

In fact, the use of multiple data sources brings remarkable results in most cases; a central issue in expanding the use of EO against environmental crimes would be to develop platforms and methodologies to integrate them with other kinds of open-source intelligence (OSINT) or human intelligence (HUMINT), as well as other technologies. Additionally, as is well known by many in the EO community, satellite data show correlation, but not causation: in this sense, in most cases satellite applications alone are not enough to prove guilt, and additional evidence is required in court.

THE USE OF SATELLITE DATA VARIES SIGNIFICANTLY DEPENDING ON THE KIND OF USERS ADOPTING THEM, AND THEIR ROLE IN ACTION AGAINST ENVIRONMENTAL CRIMES.

USERS

There are also further differences among players. National or international NGOs tend to use EO for larger issues concentrated around their thematic focus, while local NGOs concentrate on issues in their proximity, although dealing often with a variety of topics. International organisations can have a more limited scope, for instance increasing the awareness of national agencies on EO, or they can directly contribute to investigations through the analysis of data (as in the case of Interpol (International Criminal Police Organization) or UNODC, see **Case 10**).

THIS COMPLEX PICTURE ALSO SIGNIFICANTLY CHANGES DEPENDING ON SECTORS (MAIN SECTORS OF APPLICATIONS).

SECTORS OF APPLICATION

After reviewing all major sectors of environmental crime, this research has identified four areas where EO applications are the most consolidated and successful (**Main sectors**): forestry crime, illegal pollution, fishery crime and illegal mining. This research has also distinguished four areas where EO applications have a relevant impact, yet they still need further implementation (**Other sectors**): sand mining, waste trafficking, illegal construction and wildlife crime. In greater detail:

FORESTRY CRIME

- **Forestry crime** – main sectors: Forestry crime includes offenses such as illegal logging and the laundering of illegally cut timber, and is one of the most successful sectors of application for EO. While several platforms are available on the national and international level, several countries have integrated satellite analysis into their routine monitoring, such as Brazil. Forestry applications use optical but also multispectral data, to avoid the persistent cloud cover of the tropics or to detect early signs of deforestation (such as the opening of roads under the forest canopy). These advanced applications are also used to address illegal selective cutting, although the issue is more complicated to detect using satellite data, as it usually requires a higher resolution of images over wide areas. Investigations on forest fires also largely use EO (particularly in Indonesia, see **Case 3**).

ILLEGAL POLLUTION

- **Illegal pollution – main sectors**: Pollution is an issue that has been addressed by EO applications for decades, although with different outcomes depending on the kind of pollution considered. The use of satellites for the detection of oil spills is one of the most longstanding and consolidated, both to contain emergencies and to perform forensic analysis and identify the perpetrators. By contrast, soil pollution is still complicated to assess through satellite data. Air pollution is instead much easier to detect, also in relation to CO_2 and methane emissions; this capacity has however been used to a very limited extent for environmental enforcement, and mostly instead for environmental monitoring.

FISHERY CRIME

- **Fishery crime – main sectors**: Fishery crime includes all offenses related to the sector's supply chain, from illegal fishing to the sale of illegally caught fish and violations of the labour and human rights of crew members. Fishery crime has seen a significant increase in EO applications in recent times, also thanks to the growing policy and enforcement attention dedicated to the topic. In most cases, applications use SAR data to detect dark vessels, i.e., boats that have no transponder active at the time of detection (Automatic Identification System, AIS, or Vessel Monitoring System, VMS). This is in most cases very effective for detecting the location of dark vessels, although it gives little information about the activities in which such vessels are involved. Additional data are thus needed in investigations, although the locations and movements of dark vessels could also provide a great deal of information: ports where illegally caught fish is unloaded, areas where ship-to-ship transfers take place, for instance.

ILLEGAL MINING

- **Illegal mining – main sectors**: Illegal mining is a sector where EO is already consolidated, but where also applications are rapidly expanding. EO has been used for years to detect fully illegal mines, particularly Artisanal small mines (ASM) in the Amazon (**Case 10**). This is also a typical case of crime convergence, where illegal logging, illegal mining and the production of drugs are done in the same location and by the same criminal groups. However, EO has also been used on a number of occasions to detect the illegal activities of apparently legal businesses: pollution, expansion of activities beyond the concession, use of illegal practices, or involvement in nearby illegal mines (by, for instance, providing them with equipment). These applications also extend to the trade and refining of minerals, and have been applied in a number of high profile cases, particularly in Southeast and Southern Asia (**Case 2**) and in Mexico.

SAND MINING

- **Sand mining – other sectors**: Sand mining is a major issue (considered by Interpol to be the second environmental crime globally in terms of economic value), but it has been receiving significant attention only in recent times. EO applications can prove useful, but currently they are mostly employed to understand the impact of illegal extraction. This is also because illegal sand activities are in several cases done by relatively small boats and during the night, which makes satellite detection particularly difficult.

- **Waste crime – other sectors**: Waste crime is one of the most common and relevant instances of environmental crime worldwide, and it is central to the enforcement activities of agencies worldwide. However, EO applications are in several cases still under development, since algorithms in most cases lack the accuracy to detect small illegal dumping sites, and EO is not particularly fit for the detection of vessels or trucks carrying illegal waste. Nevertheless, systems such as those recently developed by the POLIMI university of Milan (**Case 9**) have shown a remarkable success rate and operative effectiveness for the detection of illegal waste disposal and even for illegal waste trafficking.

WASTE CRIME

- **Illegal construction – other sectors**: Illegal construction is a consolidated environmental offense with a strong impact on the landscape and the territory, now exacerbated by the climate crisis. EO applications could be particularly effective as they provide a clear picture of the landscape, and would not require very high resolution to detect changes. However, the implementation of applications is still much below its potential, likely because the issue has always been considered an administrative instance with little need for advanced investigative techniques.

ILLEGAL CONSTRUCTION

- **Wildlife crime – other sectors**: Despite being one of the most relevant and perhaps the best known environmental crime worldwide, EO applications are usually limited for issues such as wildlife trafficking or poaching, as detection would require a very high resolution matched by a very frequent revisit time. This in turn would make the application expensive and complicated to set up, even compared to traditional monitoring. However, new applications are now being developed that do not aim at detecting poachers or wildlife, but at using EO to identify risk factors and areas where the risk of wildlife crime is greater (**Case 8**). These applications are very effective, but require a significant integration of different kinds of data and intelligence.

WILDLIFE CRIME

CONCLUSIONS AND RECOMMENDATIONS TO IMPROVE EO EXPLOITATION FOR CRIME-FIGHTING APPLICATIONS

The use of satellite EO data against environmental crimes has expanded rapidly over the years, but has not yet reached its full potential. This is generally true worldwide but even specifically for the countries in which use is most advanced. As discussed in the **Main obstacles** section, while further technical advancements in terms of available missions and new tools will definitely contribute to new and more effective applications, operative, legislative, judicial and even political issues need to be addressed first and foremost (**Main obstacles – Political obstacles**).

This research has identified a few crucial suggestions that could address such obstacles and empower EO applications against environmental crimes, with an impact already in the short and medium term. These recommendations are general and directed to all players in the environmental crimes sector, from policymakers to enforcement agencies, NGOs and space agencies. Specifically:

BENEFITS IN THE USE OF EO ARE MAXIMISED WHEN THERE IS UPTAKE WITHIN THE ORGANISATION.
In most cases, EO applications are used for single cases by agencies that are particularly aware of their potential, or even by individuals who for different reasons have some EO expertise or have been in touch with people that have. In others, they are directly approached by international organisations, by research centres or by NGOs that have developed applications suitable for use in enforcement action. However, these uses are generally limited to one-off trials and are rarely replicated to other sectors or other regions. The situation is so fragmented that we found that EO solutions are at risk of being “forgotten” whenever the people with the relevant expertise leave their position (which frequently happens in police forces). Such applications require updatability and consistent management to address new criminal methodologies or changes in the sector or in regulations, which in turn requires medium- to long-term planning. Without consistent planning, satellite applications usually fail to make a persistent contribution.

Instead, countries and agencies that have structurally integrated the use of EO in their action against environmental crimes have witnessed the greatest results: this is usually achieved for instance through the enactment of policies specifically dedicated to mainstreaming EO across environmental enforcement and monitoring (ideally through dedicated and standardised procedures) by designing environmental policies that already include (and oblige the use of) EO tools, and by promoting continuous and structured capacity building. This is the case for instance in Vietnam, which has a dedicated National Remote Sensing Centre performing coordinated analysis of satellite data also for environmental enforcement agencies, across all sectors. It is also true of Costa Rica, whose administrative environmental tribunal obliges all prosecutors to perform a preliminary satellite check on the location of each case to gather initial information. The structural application of EO offers several benefits: it increases the deterrence effect, as people are more aware of the ongoing monitoring once it becomes embedded in enforcement action, it allows organisations to scan high-risk locations in advance to detect early signs of offenses, and generally speaking it also significantly expands the use of EO to less-aware institutions.

It is worth adding that structural application of EO works best when it is associated with legislation imposing its adoption; this has been the case for instance for the EU Deforestation-free Regulation (EUDR), which obliges European importers of key agricultural commodities to develop tracing mechanism to prove the goods are not linked to deforestation. Several producers of crucial products such as coffee or soy have indeed developed efficient tracing systems that were considered too expensive or complicated before the enactment of the EUDR.

THE AVAILABILITY OF FREE, USER-FRIENDLY THEMATIC PLATFORMS FAVOURS THE ENGAGEMENT OF NON-EXPERTS.
This is another crucial point for expanding the use of EO against environmental crimes: while platforms such as Copernicus Browser have made available and accessible an unprecedented amount of data, they remain complicated to use for most people without Geographical Information Systems (GIS) expertise. Police officers have also scant time and resources to gain such skills, and are thus unable to access the premier platforms. Platforms that are perceived as more familiar or easier to use have instead been adopted much more extensively and continuously, despite offering less information or being less accurate than the more complex counterparts: this is the case for Global Nature Watch, for instance, or of the Global Fishing Watch Map. Most notably, several agencies, such as the Cape Town firefighters (Interview 33) or prosecutors from Costa Rica (Interview

16) have been using Google Earth and Google Earth Engine in their work, because of the similarity of the app to others that they use daily. A priority for service or data providers should therefore be to develop platforms that offer at the same time the huge endowment of free data available at the moment, and the ease of use, familiarity and even loading speed of popular platforms. This should include automated versions of the most used analytical tools (such as systems for the detection of changes in the landscape), possibly with a native design for both desktops and smartphones. The ultimate aim would be to develop an accurate and complete tool, that even an officer or an employee in an environmental agency with no training or interest in EO could almost immediately use.

ENFORCEMENT AGENCIES AND THE JUDICIARY WOULD BENEFIT FROM MORE AWARENESS-RAISING ACTIONS.

While academia, civil society and international organisations generally have a sufficient level of awareness on EO applications, this is usually not the case for enforcement agencies or most especially for judges and prosecutors. Developing an internal capacity to analyse satellite data within agencies would likely be the most efficient way to address this issue, for instance through the creation of technical units specialised in remote sensing and other crucial technologies, as in the case of the Spanish Nature Protection Service (SEPRONA), the environmental enforcement component of the Spanish Guardia Civil, or for the environmental administrative court of Costa Rica. This is however complicated for several countries, due to a lack of funding or organisational hurdles; nonetheless, capacity building, as well as enhanced cooperation with international agencies and with civil society could significantly improve the situation.

Other recommendations are the following:

- **Action should take into account not only consolidated features of environmental crimes**, but also (and perhaps mostly) emerging trends and crimes. For instance, crime convergence is becoming a major issue that is now extensively considered in investigations, and should therefore be considered in developing new EO applications, or when expanding old ones. New crimes are also arising due to global economic trends, such as illegal mining for critical minerals or sand mining; understanding such trends could help develop timely EO applications and enable rapid action.
- Complexity is sometimes necessary, but has its drawbacks, and sometimes easier solutions may be more effective. Applications that combine

different sensors (optical with atmospheric signals, for instance) or that perform any kind of advanced analysis in a manual way can be difficult for non-specialists to use, or even for people with little expertise on the specific project, and this can lead to the abandonment of tools. Automation is key to fostering the use of more advanced solutions.

- **There will be a growing need for "last mile translators", able to bridge between data and users**. In many cases the sector is still missing tools that are built for environmental investigators, and several of the available platforms either lack dedicated tools for specific sectors or, most importantly, are not particularly user friendly; in some cases applications have insufficient understanding of police procedures, or even have jargon and workflow quirks that discourage non-expert users. This is the result of a variety of factors: above all, environmental crimes are a relatively new category in relation to EO applications, sectors are quite varied, and the number of players is equally heterogeneous. In this sense, "last mile translators" able to bridge the gap between the data and the final user are needed to stimulate usage, a role that at the moment is mostly covered by NGOs and a few institutions (such as WRI for Global Nature Watch). Projects that involve end users in designing and testing will also offer a great contribution, as in the case of ESA's EO4security[1].
- **Promote international collaboration**: Most environmental crimes have a transnational component, yet action is fragmented among national agencies, and in some cases even among local ones, with little coordination or exchange of information. EO is a transnational tool by definition, but is very rarely used in multi-national cases due to this lack of cooperation. It will be crucial to promote the use of EO in international cases, possibly through the cooperation of entities such as Interpol or UNODC.

In conclusion, based on the extensive research in the field, interviews and desk research behind this report, this analysis found that EO is one of the most employed technological tools globally against environmental crimes, and that its usage has increased exponentially in the past decade thanks to a greater endowment of data and analytical tools. Nonetheless, the overall usage is still widely under its potential and, above all, scarcely employed in promising sectors (sand mining and illegal construction, for instance) and by some players (judges and prosecutors in particular), due to a variety of factors – the lack of legislative frameworks and policies structurally implementing EO in action against environmental crimes being one of the most relevant causes.

1. ESA website: **EO4security**.

Reforestation in the Monteverde Cloud Reserve of Costa Rica. Contains modified Copernicus Sentinel data (2026), processed by ESA.

GENERAL ANALISYS

1. FUNDAMENTALS OF SATELLITE EO USE AGAINST ENVIRONMENTAL CRIMES

This report sits at the intersection of two topics: environmental crimes and Earth Observation (EO), two areas often requiring dedicated expertise. This section therefore provides a series of crucial notions needed to understand more advanced findings concerning the two sectors. While not aiming at being fully exhaustive for either category, the section is intended to provide the groundwork for understanding of the rest of analysis – for experts in each of the fields, as well as newcomers to both. To that end, this section covers the essentials of both domains, environmental crimes and satellite EO, before exploring how they intersect, from the earliest applications to the current state of play.

1.1 INTRODUCTION TO ENVIRONMENTAL CRIMES

1.1.1 A definition of environmental crime

The category of “environmental crime” encompasses a vast series of violations across a variety of sectors, often quite different from each other. Compared to other kinds of crimes, such as crimes against the person, environmental crime has only been recently considered as a distinguished category with a value per se, and was instead ancillary to other offenses (such as economic or property crimes).

Working on an envicrime definition

Because of its heterogeneity and novelty, international organisations have been working on a common definition of environmental crime only recently, and to some extent there still is a degree of confusion among different institutions (usually stemming from different perceptions). As an example, the EU, one of the most advanced entities in the global fight against environmental crimes, has not chosen to adopt a definition of environmental crimes, even with the new Environmental Crime Directive, adopted in April 2024 (European Parliament and Council of the EU 2024a); prior to that, not only the old 2008 Environmental Crime Directive, but even the original 2021 proposal for the new one (European Commission 2021a) did not include a shared definition. China does not have a general definition in its legal system as well, but only individual definitions for single offenses (Zhou et al. 2024), while the US definitions change from institution to institution[2].

Generally speaking, this report considers “environmental crimes” as all activities that are illegal and harm the environment, following the definitions enacted over the years by organisations such as the EIA (Banks et al. 2008), UNODC[3] and Interpol[4]. The sectors included in this definition are thus quite large, and evolving: the 2008 EIA report (one of the earliest with a comprehensive approach to the topic) only considers illegal trade of wildlife, illegal trade in ozone depleting substances, illegal dumping, illegal, unregulated and unreported fishing (IUU), and illegal logging and timber trade (Banks et al. 2008). It misses key areas such as illegal mining and the illegal exploitation of natural resources (particularly illegal water extraction), which are integral to this analysis.

As the whole environmental crimes sector is expanding and evolving, the approach taken by most institutions is currently to switch from a focus on individual topics (illegal logging, illegal mining, etc.), to a more comprehensive perspective: leading institutions such as UNODC and Interpol now

2. Energy and Natural Resources Division website: Environmental Crimes Section and FBI website: Environmental Crime.
3. UNODC website: Explainer: What are crimes that affect the environment?.
4. Interpol website: Environmental crime.

consider environmental offenses as a single category, where criminal players and methodologies are often interconnected, instead of different and separated instances (Interviews 6 and 8).

1.1.2 Main trends in environmental crimes

This is a moment of rapid and crucial evolution for environmental crimes.

Environmental offenses are, first and foremost, witnessing the fastest expansion among all crime areas, with an increase between 5 and 8 per cent of their value each year (UNODC 2025) . Estimates are however very wide and, to some extent, unreliable, as data deficiency is likely one of the major issues in addressing environmental crimes. Some sectors are however more affected than others: while illegal mining is growing because of the increased demand of minerals due to the energy transition and digitalisation, wildlife trade has been steady in recent years (Colantoni et al. 2022a) . Nevertheless, the perception shared by almost all actors (such as enforcement agencies, civil society, international organisations) in particularly affected regions (such as the EU, Sub-Saharan Africa, South East Asia, Latin America) is that the whole phenomenon is indeed facing an unprecedented expansion (Colantoni et al. 2022a).

The causes behind the rise

This trend is due to a variety of reasons: OCGs are increasingly involved because of low sanctions and high profitability of illegal waste, timber or wildlife trafficking, compared to arms or drugs trafficking. Growing environmental regulations are leading companies to resort to illegal practices for waste disposal or for sourcing raw materials – one of the main causes behind the growth in white-collar crimes among environmental offenses – since they offer a much cheaper alternative and avoid adding further costs to businesses. To some extent, growing efforts by enforcement agencies and new technologies are also allowing for an increased detection rate in almost all sectors.

New tools to fight environmental crimes

This complicated situation is however matched by a renewed political attention to the issue, and by a new set of technological, economic and social tools that could overturn this global wave of environmental crimes. While the advancement of environmental awareness and regulations in the past years has helped increase the attention given to environmental crimes, in recent times global institutions have started focusing explicitly on the topic: in 2022, the EU has included for the third consecutive time environmental crimes as a priority in its European Multidisciplinary Platform Against

Criminal Threats (EMPACT), the leading European platform for cross-cutting coordination against crimes[5]. UNODC has also increased its focus on the topic, having recently published its first Global Analysis Against Crimes that Affect the Environment in 2025 (UNODC 2025). This has been accompanied by similar efforts from agencies such as the UNICRI, Europol, Eurojust and Interpol, by a significant number of national governments inside and outside Europe, and even by the involvement of many from the private sector (particularly but not exclusively companies working in the trade and shipping of natural resources) (Colantoni and Sangiorgio 2024a, Colantoni et al. 2022a). This renewed attention is supporting the development of new initiatives, such as Eco-Solve, a GI-TOC programme focused on addressing the data deficiency issue[6], as well as expanded resources, which could be crucial to enable the implementation of new technologies. Indeed, both satellite imagery analysis, and a variety of other tools could revolutionise the approach to environmental crimes: drones offer a readily available and cheap option to obtain high-resolution aerial images, while apps and online platforms now represent a quick and efficient tool for commodity tracing and for the integration and comparison of data. Other experimental technologies, such as DNA and isotope scanners, could be a game changer for sectors that have failed to address violations for years, as in the case of illegal logging and timber trade (Colantoni et al. 2022b).

1.2 INTRODUCTION TO SATELLITE EARTH OBSERVATION

A definition of EO

EO satellites are artificial, space-based platforms orbiting around the planet to collect data on the Earth's atmosphere, land and oceans. They use different types of sensors to measure electromagnetic radiation reflected or emitted from the surface. By knowing the radiative "signature" of different bodies, such as vegetation, soil or gases, it is possible to infer key geophysical parameters about them with remarkable accuracy. In some cases, this information comes in the form of an image, either close to what the human eye normally sees, or showing information that is otherwise invisible. Depending on the characteristics of the sensor and of the platform, EO missions can be best suited for different types of applications, such as environmental monitoring, weather forecasting, disaster management or territorial mapping.

1.2.1 Different types of satellites and data

There are several types of satellite data; each type has its own characteristics that can be best suited for different types of applications. Indeed,

5. EUROPOL website: EMPACT.
6. Global Initiative Against Transnational Organized Crime website: Eco-Solve.

satellites are equipped with different sensors depending on the purpose of the mission; for this reason, it is important to understand the peculiarities of different types of data to comprehend which one is the best fit to monitor each environmental crime. Here below, a brief summary of the main types of sensors and corresponding data types.

Optical

This type of data is the most common. Indeed, when the general public thinks of satellite images, they typically envision this type of imagery: similar to aerial images but from a higher altitude. Optical imagery is captured using visible light, which can be perceived by the human eye. However, the primary limitation of optical sensors is their dependence on favourable atmospheric conditions and solar illumination, i.e., they cannot be used in darkness or through clouds. They are the most straightforward to understand and use, and are particularly effective to monitor offenses such as illegal mining or for forest monitoring in temperate regions, where the atmospheric conditions allow, although usage is particularly wide (ESA 2020a).

Thermal Infrared

These data provide information about heat signatures rather than reflected light; they remain susceptible to atmospheric interference such as heavy cloud or fog, but can be seen also at night. Mainly used to measure temperatures of land and sea surface, or to monitor open sea illegal fishing or wildfires.

Hyperspectral

These data portray hundreds of spectral bands that are not detectable by the human eye, enabling the creation of a richer picture. With respect to optical data, for instance, they can identify subtler changes in the colour of vegetation, enabling the possibility of inferring the state of health of a forest, or examining the level of bare soil pollution, crop varieties or subtle vegetation stress (Njambi 2026).

Synthetic Aperture Radar (SAR)

Unlike the passive satellites described above, SAR is an active system that transmits its own electromagnetic pulses toward the Earth's surface. Because these microwave pulses penetrate clouds and operate independently of sunlight, SAR provides a reliable “all-weather, day and night” monitoring capability. However, the resulting data are monochromatic and complex, requiring specialised analysis to interpret the patterns accurately. They are used in tropical regions where persistent cloud cover makes optical images unreliable or for dark vessel detection, particularly valuable since illegal fishing often occurs at night or in poor weather conditions that would render optical satellites useless[7].

LiDAR

LiDAR satellites can precisely measure the distance to the object and its condition by emitting light in the visible to near-infrared range and measuring the strength and time to reflect back from the object and the wavelength. They can generate accurate 3D model representations. Mainly, these satellites can scan the surface ignoring the vegetation cover and even buildings, but they can also measure tree height in the forest, ice sheet thickness and wind speed[8].

In addition to the above, there are other key characteristics that determine the suitability of a satellite system for environmental crime monitoring (see more detailed information in **Table 1**). These depend on the joint characteristics of the sensor and of the satellite platform (e.g., its orbit) and can be summarised as follows (please refer to the **Glossary** for further definitions and terminology).

Spatial Resolution

This is defined by the size of each pixel within a digital image and the area on Earth's surface represented by that pixel (e.g., 10m resolution means that 1 pixel represents 10m x 10m)[9]. The smaller the number, the higher the resolution. The most advanced systems commercially available today have 0.3m resolution.

Temporal Resolution/Frequency

This is the time it takes for a satellite to cover the same observation area (e.g., Sentinel-1 has a six-day temporal resolution, meaning it can capture the same location every six days), either by passing again on it on the same track, or using steering, tilting, or wider sensors. This parameter also depends on geographic position: for near-polar orbits the revisit frequency increases, while it decreases near the equator. For crime detection, this determines how quickly authorities can document an incident after it occurs, such as the probability of detecting the ignition point in a fire before it develops.

Satellite missions can be operated by public and private entities. Typically, space agencies such as the US National Aeronautics and Space Adminis-

7. JAXA website: Radar Imagery.
8. NASA Earthdata website: Active instruments.
9. NASA Earthdata website: Resolution.

tration (NASA) and ESA provide large-capacity environmental space missions while private companies concentrate on profitable applications such as very high resolution optical missions.

TABLE 1: SATELLITE CHARACTERISTICS

	Example Mission	Spatial Resolution	Temporal Resolution at the equator	Environmental Crime Applications	Data Providers
Optical - HR	Sentinel-2 (ESA)	10m	5 days	Illegal logging Land-use change	Public
Optical - VHR	WorldView (Vantor)	<1m	Daily	Illegal waste dumping Illegal mining	Private
SAR - HR	Sentinel-1 (ESA)	10-20m*	6 days	Oil spills Illegal fishing	Public
SAR - VHR	ICEYE/X2	<1m	Daily	Illegal construction Tropical forest monitoring	Private
Thermal Infrared (IR)	Landsat-8 (NASA)	100m	16 days	Wildfire detection Vessel detection	Public
Multispectral	PRISMA (ASI)	30m	29 days	Water contamination Soil pollution	Public
LiDAR	GEDI (NASA)	**	On Demand	Illegal logging Canopy changes	Public

* Depending on the operating mode. ** LiDAR spatial resolution is defined by pulse density and footprint diameter rather than fixed pixel dimensions.

EO satellite data are typically made available to users through data access platforms. In some cases, they also have some analytical tools and/or provide data that has already been at least partially processed (e.g., corrected for geometric distortion or atmospheric absorption).

Depending on the type of application, EO data are generally used in integration with other types of data. In fact, by merging different types of EO data and/or different types of data sources and with advanced processing (including AI), remote sensing experts from universities, NGOs and private companies are capable of elaborating further information that is then made available to the public for free or under commercial license.

1.3 INTRODUCTION TO THE USE OF SATELLITE EO AGAINST ENVIRONMENTAL CRIMES

Overview of EO usage

Satellites have been employed in fighting environmental crimes at least since the 1980s–90s, although in the past this was done mostly in relation to specific occasions and with significant limitations. Indeed, for the first two decades, usage was scarce and lacked a systematic approach; this started to change in the early 2000s and particularly in the 2010s, when countries like Brazil extended their satellite monitoring to enforcement activities, and when the Sentinel missions significantly expanded the continuous availability of data. In the past five to ten years applications have finally surged, and even smaller countries like Costa Rica or Belgium (Interviews 16, 36 and 37) have started to systematically adopt satellite applications (also thanks to a significant expansion not only of the available hardware (i.e., the satellite missions), but also of the software for data analysis.

1.3.1 A brief history of the use of satellite EO against environmental crimes

Early applications: NASA and the Charter

The launch of NASA's Earth Resources Technology Satellites Program in 1972, which became the current Landsat in 1975, offered for the first time a comprehensive set of data concerning the Earth's surface, and which could also be used to see the impact of human activities on land and sea. While the employment of such data in terms of land use or natural resources, and general environmental monitoring, has been steady since the launch of the Landsat programme, their application against environmental crimes has been limited over the decades. Several factors influenced this trend: mostly the insufficient availability of data (also because of the lack of online platforms and the impossibility of access for the general public), the low frequency and spatial resolution of Landsat imagery, as well as the scarce global awareness on environmental crimes in the 80s and 90s. Indeed, in relation to past environmental crimes, satellite data have been almost entirely used only for major disasters, the first recorded use being likely the 1982 Chernobyl nuclear accident (De Bruijn 2024). One of the early initiatives linking environmental crimes and satellites was the International Charter Space and Major Disasters (usually known as "the Charter")[10], founded by the ESA, the Canadian Space Agency (CSA) and the Centre National d'Etudes Spatiales (CNES), the French Space Agency, in October 2000. Now counting 17 members, the initiative supports countries affected by natural disasters such as landslides, fires and oil spills by promoting coordination among space agencies and the rapid supply of crucial satellite data to understand the damage and take countermeasures. It however only focuses on humanitarian assistance and has played a small role in relation to environmental investigations so far.

10. The International Charter: Space and Major Disasters website: Satellite data to support disaster response worldwide.

Focus on the Charter

Indeed, satellite data have been mostly employed in the past for environmental monitoring, with limited attention to environmental enforcement. Although the situation has improved, this is still valid across sectors and countries. Satellites were however already being applied in some areas of environmental crime in the 90s and the 2000s, partially thanks to the influence of the Charter (Jones et al. 2015). Oil spills have been one of the earliest activations of the Charter and, more generally, one of the first uses of satellites against environmental crimes. While the focus of the Charter activities is and has always been on limiting the impact of disasters, in this case by monitoring the spread of spills, such uses laid the foundations for future applications with a greater enforcement perspective (as in the case of the European Maritime Safety Agency's CleanSeatNet, launched in 2007)[11]. This expansion of the Charter's focus also took place (although to a lesser extent) in the case of the collapse of dams containing mining tailings; however, despite the topic being a crucial one for the Charter, the tool was activated for this reason for the first time only in 2010 (for Ukraine)[12], and on two occasions in 2015, regarding the Fundao and Samarco dam disasters in Brazil[13]. Fires have also been a frequent occurrence of activation of the Charter since its launch, but with no known application linked to enforcement – in the case of the dam collapses, however, satellite photos were used in the subsequent investigations by the Brazilian authorities (which, however, have been inconclusive in all cases considered).

A turning point: Brazil and DETER

Satellites have been used to track deforestation since the 1980s, but applications focused on preventing illegal logging and enforcing forestry regulation have only gained traction since the early 2000s. Brazil led the way: the astounding rates of deforestation of the 1980s and 1990s convinced the Brazilian government in 2002 to publish the deforestation data of the national space agency (INPE) that were originally only for internal use (collected through the PRODES system, which used Landsat 5 and 7 data) (NASA Earth Observatory 2019). In 2004 this led to a much more ambitious decision, the launch of the bold Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm)[14]. Among other tools, the plan integrated satellite observation into enforcement action; this objective was achieved through the launch of another satellite-based system, DETER, which unlike PRODES, did not collect data on a weekly basis, but provided information on fires and clearings daily. Although of a lower quality, this information was used to coordinate field action by officers, who could employ the data to restrict the areas where

11. EMSA website: CleanSeaNet – European satellite based oil spill monitoring and vessel detection service.
12. The International Charter: Space and Major Disasters website: Potential collapse of a tailing pit dam, Ukraine.
13. The International Charter: Space and Major Disasters website: Dam collapse in Brazil.
14. Climate Policy Database Website: PPCDAm Brazil.

they would investigate suspicious activities (illegal gold mining, drug production, illegal farming) (NASA Earth Observatory 2019). Such use significantly improved the enforcement activities of the Brazilian police, and set up the basis for the current more advanced and accurate analysis, which now also involves non-optical images and particularly synthetic aperture radar (SAR) data.

Copernicus programme

One of the most crucial expansions in data availability starts in 1998, when the Baveno manifesto envisaged a new programme called Global Monitoring for Environment and Security (GMES) (Brachet 2004), which ultimately led to the creation of the Copernicus programme. The manifesto pushed for an increased capability for Earth monitoring from space, and for more coordinated efforts by European countries, the EU and ESA on the topic. Focusing specifically on security and environmental issues, the GMES worked to deliver tools that would prove particularly useful on action against environmental crimes years later.

From GMES to Copernicus

In 2012 the name of the GMES was changed to Copernicus, while in 2014 Sentinel-1A, the first satellite of the programme, was finally launched. Followed shortly by other missions (Sentinel 2-A and Sentinel-2B respectively in 2015 and 2017, Sentinel 1-B in 2016), the start of the Copernicus programme represented one of the largest expansions of EO data availability globally for the fight against environmental crime. Indeed, the EU's Copernicus programme offers an end-to-end solution spanning the entire EO supply chain, making it one of the most accessible and comprehensive resources available for environmental crime monitoring. All Copernicus data and services are free and open access, removing the cost barrier that limits the use of private satellite providers for NGOs, enforcement agencies and prosecutors. Copernicus operates at two levels relevant to environmental crime investigation.

Data and platform availability

The Copernicus Browser provides direct access to satellite imagery. Users can select any location and time window, enabling straightforward before-and-after comparisons, a core technique in documenting environmental crimes. An enforcement officer or field investigator can, for example, retrieve imagery of a specific forest area over a multi-year period to document the progression of illegal logging, or compare pre- and post-event images to establish the extent of illegal land clearing or the spread of contamination following an illegal industrial discharge. The tool requires minimal training, making it accessible beyond technical teams[15]. By standard-

15. Copernicus Data Space Ecosystem website: Copernicus Browser.

ising datasets spanning decades, these services enable pattern analysis and long-term monitoring, key elements for building evidentiary records of persistent or repeat environmental offending[16].

In addition, the so-called Copernicus Services provide specialised ready-to-use information for end users and public administrations that include maps, reports, early warning and forecasts. In particular, the Land Monitoring service supports monitoring of deforestation, illegal land use change and habitat destruction. The Marine Environment Monitoring service provides information about the status of oceans and on a variety of different physical, biological, and climate variables. The Atmosphere Monitoring service tracks air pollution plumes that may indicate illegal industrial activity or waste burning. Finally, the Security service provides Support to EU External and Security Actions (SESA), making available a vast array of information on issues affecting the EU's security, with a dedicated focus on environmental governance[17]. Member states can request the assistance of Copernicus on specific cases, such as monitoring waste disposal, and the production of a "Briefing Note" containing a detailed set of geospatial information resulting from satellite analysis[18].

1.3.2 AThe current landscape: More and better data

In recent years, the framework of application has evolved significantly at the global level. This shift has been driven by several interconnected developments, particularly a broader surge in political attention and legislative action against environmental crimes (discussed before) and the following elements:

- The increase in quantity and quality of EO data
- The emergence of accessible, user-friendly thematic platforms
- The growing involvement of the private sector
- The integration of AI into image processing and analysis

Generally speaking, thanks to the above factors usage has significantly changed and evolved in the past 15 years. This is very evident when compared to applications in 2012, extensively reviewed at the time in the study "Evidence from Space" produced by the London Institute of Space Policy and Law (Kay et al. 2012). The report performs an encompassing review of applications (missing however a focus on forestry crime), but only reports individual cases. A systematic, structural use of EO by environmental and enforcement agencies, such as those described in **Case 4** and **Case 6**, are

16. Copernicus main website: Copernicus Services.
17. SESA website: Environmental Compliance.
18. SESA website: Briefing note.
19. Sentinel Online website: International cooperation - Partners.

completely missing since the limited availability and cost of data made this almost impossible at the time. Indeed, the study makes frequent references to issues related to low resolution of images (page 21) and scarcity of usable images (page 116), lamenting that high and very high resolution data were at the time almost only available for military purposes. In this sense, the comparison between the 2012 study and this research reveals that, while usage in courts has not particularly changed (and indeed remains significantly low), operative applications have massively expanded.

The increase in quantity and quality of EO data

Free data from the Sentinel missions

The launch of the European Union's Copernicus programme in 2014 has been one of the most relevant changes in terms of satellite data availability not only on the European, but also on the global level. The bulk of data for Copernicus comes from the Sentinel missions, whose first launch with Sentinel-1A in 2014 was concomitant to the start of the programme. The programme, however, also receives or even buys commercial data to complement Sentinel data when needed (e.g., VHR in case of emergency), additional data from the so-called Copernicus Contributing Missions, i.e., missions by national, European and international organisations, as well as private companies, that were not specifically dedicated for Copernicus but contribute to it. The launch of Copernicus has likely been the most relevant breakthrough in terms of data availability since the start of Landsat: it is the only other existing source of free, easily accessible, worldwide and frequently updated satellite data available at the moment. Not only does this represent an unprecedented expansion of the data available from Landsat, but Sentinel satellites also offer features that complement and, in some cases, expand the information provided by Landsat. Sentinel sensors have, for instance, a spatial resolution of maximum 10 meters (as opposed to 15 meters for Landsat-9) and 13 to 25 spectral bands (instead of 8-11).

NASA and ESA also cooperated when the latter was developing the Sentinel missions in the years before the launch of Sentinel-1B in 2016, to improve the interoperability of their systems – this has been for instance the case for Sentinel-2A (ESA 2013). International cooperation on Copernicus has been further strengthened by the European Commission with a series of 17 cooperation agreements[19].

Role of national agencies

In the past two decades, several individual countries have also launched their own EO satellites, both those with a consolidated history of applications (e.g., India, Brazil) and those that were less familiar with the sector (e.g., Algeria, Turkey). This trend has further increased the availability of data from a domestic but also an international perspective, since several of these national space agencies share cooperation agreements to integrate their data, and some also make them freely available on platforms and websites similar to Copernicus' and Landsat's. This is for instance the case for the Korean KOMPSAT-2A meteorological satellite (eoPortal 2024)[20]. It is worth noting however that the availability and usability of these data are varied and usually significantly lower than is true of Copernicus and Landsat. Japan's data from the four ALOS satellite missions are for instance only partially available, and public access has only been granted recently[21].

The emergence of accessible, user-friendly thematic platforms

Together with the development of new space infrastructure, the current advancement of EO has also been supported by a significant advancement in the analytical capabilities to extract information from EO data and a proliferation of dedicated services, tools and platforms for the analysis, integration and dissemination of satellite data – and thus for their potential employment against environmental offenses.

Role of public providers

The expansion of satellite-related applications is perhaps the fastest moving area among all considered in this report, and this evolution is still, to some extent, unclear and undefined, and will require rapid legislative action to be supported (see **Certification of satellite data**). Public providers and space agencies invested heavily in stimulating the development of innovative solutions that exploit satellite data or in providing public services (such as those from the Copernicus programme). In parallel to these publicly funded projects, there is a growing wealth of independent EO-based services and products, with remote sensing specialists within research institutes, NGOs and commercial companies providing so-called "value added" services or products translating EO data into actionable information.

Thematic platforms exist that offer tools for both basic or advanced analyses, in most cases automated and focused on specific applications. These platforms sometimes integrate the use of AI to automate detection processes or other kinds of analysis (such as identifying land-use change), and use, in the majority of cases, the data offered by Copernicus, Landsat and, to some extent, also by other national agencies. These products or platforms may require different levels of expertise, depending on the type of information required or on the type of data.

20. For the platform see: National Meterological Satellite Center of KMA.
21. ALOS website: ALOS-2 PALSAR-2 ScanSAR Products.

It is interesting to notice that in recent years giant data providers such as Google, Amazon AWS and Microsoft are also offering access to Landsat and Copernicus data on their platforms, as well as from other national agencies (European and extra-European) and private providers, such as Airbus (Gorelick et al. 2017). Although their analytical tools remain limited, and they rely on the same data available through platforms like the Copernicus Browser, users are generally more familiar with these interfaces and therefore more likely to access them, significantly extending the reach of satellite data. For instance, Google Earth's "timelapse" option, showing high-res data with a frequency of once every one to three years (for the last decade at least), has been reported to be increasingly employed by administrative courts and agencies for preliminary checks on open investigations (despite having often a very limited amount of data available) (Interview 51).

Thematic platforms

Specifically with relevance to the use against environmental crimes, various examples have been found of platforms specialised on specific types of crime. These thematic platforms have some limitations in terms of accuracy, time and geographical coverage compared to ad hoc applications developed for specific cases, or even to analysing data through more complete platforms (such as Copernicus Browser). However, they are among the tools most employed by environmental experts and activists, as they are free, easy to ease, accessible and require little to no training (Interviews 4, 5, 11 and 20).

For instance, the Global Fishing Watch Map displays global fishing activities from 2012 to the present, with over 100,000 commercial fishing vessels monitored. Users can additionally search for vessels, filter activity by flag state or time period, identify port visits and view encounters between boats. The map can be used by a variety of users, such as governments, which can take action against unauthorised vessels; researchers, who can identify the most vulnerable areas; and seafood suppliers, who can verify where and how fish are caught[22]. Another platform of this type is Global Nature Watch providing data and tools to monitor the world's forests. By using either the map, the reports or the interactive dashboards, users can be updated in real time on the status of deforestation or wildfires globally. To fast-track and make the platform compatible with the use of rangers and Indigenous communities, a mobile application of Global Nature Watch, Forest Watcher, was developed, which offers an offline functionality in remote areas without signal[23]. The Global Nature Watch platform also includes some advanced analytical tools, such as the RAdar

22. Global Fishing Watch website: Revolutionizing Ocean Monitoring and Analysis.
23. Global Nature Watch website: Forest Monitoring Designed for Action.

for Detecting Deforestation (RADD) system, which is able to detect in almost real time early signs of deforestation. Global Nature Watch indeed also allows for constant monitoring of areas users can freely draw on the map, in order to receive alerts on landscape change. Earth Ranger combines field reports with all available remote sensing data, both historical and current, to display and provide information regarding the wildlife in over 850 conservation sites. This gives a single picture of the infrastructure, enforcement resources, collared wildlife and rangers in a protected area. This tool can be used to mitigate issues such as wildlife monitoring, human-wildlife conflict mitigation, habitat protection or management of protected areas[24]. It is a tool that requires little expertise; it however needs customisation by users (providing their available information and inserting them in the platform) to be properly effective. Generally speaking, all these platforms offer wide-ranging, free tools that are a good fit with the requirements of monitoring activities and early investigations, but sometimes lack the detail and flexibility for more complex investigations.

As discussed more in detail in **EO and environmental crime legislation**, such technological advancements have however not been matched by an adequate integration into legislative frameworks. This mismatch between the speed of technology development and legislative progression is indeed one of the main obstacles to satellite use against environmental crimes.

The growing involvement of the private sector

The private sector has also contributed to this expansion. Interest in EO on the part of companies was starting already in the 2010s (Science Business 2008) and has boomed in recent years, with some estimates evaluating the share of private companies in the EO sector at around 25 per cent of the global market (Kuhr 2024). While security and defence businesses have been the first to be involved, in recent years the situation has evolved, and many companies now also focus on supporting land use planning, agriculture or mining activities. This is for instance the case for the US EO company Satellogic which, after its launch in 2010, now has 26 satellites orbiting Earth that provide data to public and private clients in over 50 countries[25]. There are also cases of “hybrid” solutions; in July 2024, the Indian National Space Promotion and Authorization Centre, an institution whose scope is to promote space projects, asked for bids or expressions of interest for the development of EO satellites (Das 2024). While the companies will receive support from the Indian state, the major share of the budget will come from private investors, and earnings will derive from the

24. EarthRanger website: Protecting wildlife and ecosystems with data-driven insights.
25. Satellogic website.

monetisation of EO data and platforms. The bid was awarded in 2025 to a consortium led by the Indian-owned Pixxel Space, and the first set of India's privately built satellites will be launched in 2027 (The Economic Times 2026).

Hybrid private-public missions

It is important to note that data from private players contribute to action against environmental crimes, but in a limited fashion compared to those provided by platforms such as Copernicus or Landsat. Most of these platforms are indeed designed for private clients and commercial activities, and collaborations with enforcement agencies or civil society are still limited. This is caused by a variety of factors, but the high cost of these platforms, the still narrow use of satellite imagery against environmental crimes, and the existence of free alternatives covering a large range of uses are among the most relevant. Hybrid, non-profit projects could however offer a better opportunity for action against environmental crimes, since they have fewer budget constraints than for-profit private initiatives, and usually have a clear task focused on a specific offense (for which they also have relevant expertise); this was for instance the case with MethaneSAT, a joint project launched by the Environmental Defense Fund (EDF), a US-based non-profit organisation, and the New Zealand space agency. The initiative was aimed at offering free, high-detail methane emissions data, which were available on a public platform[26] merging the information provided by their newly launched satellite (the core of data) with other sources (aerial, ground-based, etc.). As many countries are increasingly regulating the emissions of methane, MethaneSAT could have become a crucial tool to monitor and sanction companies breaching regulations; unfortunately the satellite suffered a malfunction circa a year after the launch and is now considered beyond recovery[27]. Future missions could however continue its detection work.

The integration of AI into image processing and analysis

Main AI developments

The recent technological advances in AI techniques have significantly changed the application of EO against environmental crimes. Artificial intelligence refers to the simulation of human decision-making capabilities in machines, such as pattern recognition. Particularly adapted to complement EO is a subset of AI, machine learning (ML), where models learn from the data and improve their performance, such as classifying land cover from labelled satellite images (Tuia et al. 2024). AI/ML provides strong synergies in improving the models for EO. AI algorithms can now autonomously process large quantities of images, identifying spe-

26. Methane Sat website: Data.
27. MethaneSAT website: Core mission to turn methane measurement data into action will continue.

cific features or changes that would be impossible to detect manually. In the context of environmental crime monitoring, these capabilities offer three distinct and concrete advantages.

Efficiency

The first advantage is time efficiency. To monitor environmental crimes, several thousand satellite images need to be checked continuously. This operation must be done promptly to intervene rapidly and prevent further irreparable damage to the environment. For human operators, the process is time-consuming, while an AI algorithm can cut the time for the task, and the monitoring can be done in near real time. As observed in the case of waste trafficking in Northern Italy, the use of an AI has cut the time of the operation by 30–40 per cent (see **Case 9**).

Accuracy

A second advantage is accuracy. In successful applications (see **Case 9**) modern AI models usually have a very high accuracy level, typically in the 85–95 per cent bracket. This value is often higher than what a human operator can obtain; this is because fatigue occurs, and the operator might be biased depending on the user's visualisation and monitoring of the images, as well as on her or his expertise.

Lastly, AI can also provide innovative solutions in addition to optimising existing methodologies. In fishery crime, for instance, it can automatically triangulate between AIS, VMS and satellite images to detect dark vessels, vessels that disable or manipulate their tracking systems to conceal illegal activity. Additionally, it can fast-track the procedural aspect of legal proceedings, as in Mexico, where the AI model developed by the NGO El Guardian Forestal automatically generates legal complaints based on the images observed, which are immediately transmitted to law enforcement (see **Case 1**).

These innovative applications are not isolated developments; they reflect a broader transformation in how AI is reshaping the entire EO industry. The downstream EO sector has witnessed a rapid expansion of AI-powered applications tailored to specific user needs. These AI/ML systems continuously improve through training on new data, creating a virtuous cycle where better algorithms extract progressively more value from satellite imagery (Buczkowski 2023).

Main obstacle to AI usage

Despite these promising developments, a significant obstacle remains: the problem of certification and validation of AI results, which must be resolved before AI evidence can be fully integrated into environmental crime prosecution. The lack of transparency stems from the difficulty in understanding the modelling process. This relates to the concept of the "black box": the data, satellite images, go in; the results, imagery analysed for environmental crimes, come out, but the inner mechanism is difficult to understand (Marco 2026). This often results in judges and prosecutors dismissing or refusing to accept cases built on AI evidence because of the lack of clarity and transparency (see **Certification of satellite data**).

Increasing data availability: The Copernicus Sentinel Expansion missions
The upcoming expansion of the Sentinel missions will also offer a further contribution to the already significant endowment of data offered by the Copernicus programme, thus also expanding its employment in the global fight against environmental crimes.

The future of Copernicus envisages the launch of six new missions in the next future: CHIME, CIMR, CO2M, CRISTAL, LSTM and ROSE-L. As each mission features different instruments and a different focus, they will likely play a diverse role in various sectors of environmental crimes.

CHIME The Copernicus Hyperspectral Imaging Mission (CHIME) will consist of two satellites (CHIME-A and CHIME-B) with a 7.5 years expected lifetime, possibly expanded to 12. The focus of this mission will be on sustainable agriculture, food security, raw materials exploration and exploitation, as well as monitoring of coastal waters and natural ecosystems. Having a hyperspectral sensor, a ground resolution of 30 meters, and a revisit time of 12.5 days, the mission will likely contribute to applications currently using Sentinel-2 data, particularly concerning illegal logging and environmental degradation. The set of products available through the mission will also likely offer further insight into land use and land pollution, and will be thus employed also for the management of agricultural subsidies and to monitor agricultural practices. Moreover, CHIME will observe routinely all inland and coastal waters (up to 37 km off-shore), thus supporting the analysis of illegal discharges, oil spills and habitat degradation of wetlands and other sensitive aquatic ecosystems.

LSTM Land Surface Temperature Monitoring (LSTM) mission will consist of two satellites with a thermal infrared (TIR), a short-wavelength infrared (SWIR), visible and near-infrared (VNIR) sensors and an expected life of at least 7.5 years. These tools benefit from high accuracy, and will be used to monitor land and soil composition, as well as evapotranspiration rates. Similarly to CHIME, LSTM will thus provide better insights in terms of land pollution and agricultural practices. Its analytical capabilities over evapotranspiration will also offer a valuable instrument to detect illegal water extraction; new applications are indeed using the parameter to detect water theft in agriculture and mining, instead of the more consolidated interferometry-based uses (which are accurate, but struggle to provide information to identify offenders, offering instead only a general picture of water consumption in the area). The LSTM mission will significantly improve on the spatial resolution of Sentinel-3, which has similar capabilities but a 1km resolution compared to approximately 50m for LSTM. The five TIR bands of LSTM are also an improvement compared to the 2 TIR bands aboard the Sentinel-3 satellites. LSTM will provide extended coverage of coastal waters (up to 100km distance from land) for marine applications, including illegal discharge monitoring, and the short revisit time (2 days with 2 satellites) will contribute to action against fishery crime.

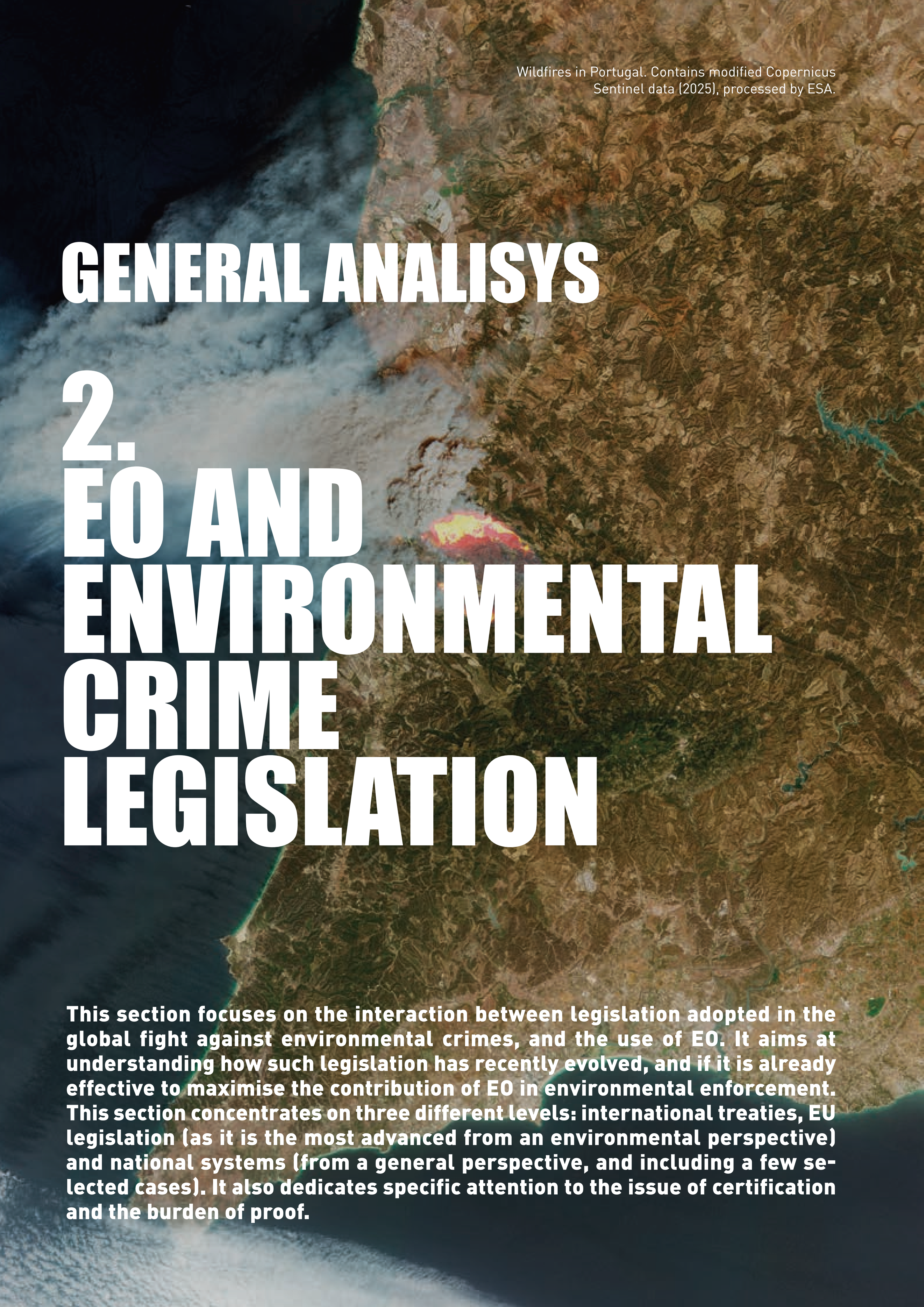
ROSE-L

The Radar Observing System for Europe in L-band (ROSE-L) is a two-satellite Copernicus mission providing systematic L-band SAR observations over land, oceans and ice. The launch of the first satellite is expected in 2030. ROSE-L will complement Sentinel-1 with frequent, day-and-night, all-weather observations at a higher spatial resolution of 5 m × 10 m. The mission will provide a global revisit time of six days, increasing to three days over Europe and to daily coverage over Arctic regions.
The longer L-band wavelength will enable improved penetration through vegetation canopies and greater coherence over densely vegetated areas, supporting the monitoring of forests and ecosystems vulnerable to illegal logging, deforestation and other environmentally damaging land-use changes. ROSE-L will also greatly support the already significant uses of SAR data against environmental crimes at sea by enhancing vessel detection, monitoring of human activities at sea, including illegal fishery, and observation of pollution events.

CO2M

The Copernicus Carbon Dioxide Monitoring (CO2M) mission will carry instruments with the capacity to monitor emissions of carbon dioxide and methane; the mission will likely be a groundbreaking instrument for climate action, since such tools are largely missing (particularly after the MethaneSat failure) and emissions data are in most cases the result of more or less accurate estimates. This will greatly improve the understanding not only of global emission trends, but also individual responsibilities by medium and large emitters. This will not have a short-term impact on action against environmental crimes, since CO2 and methane emissions are not yet included in enforcement action against polluters (as opposed to, for instance, PM2.5). However, as regulations are rapidly progressing, particularly regarding methane emissions, CO2M and similar missions may play a role in environmental enforcement already in the next five to ten years. The mission will consist of three satellites, with an expected life of 7.5 years. The constellation will be launched in 2027, 2028 and 2029.

The Copernicus Polar Ice and Snow Topography Altimeter mission (CRISTAL) and the Copernicus Imaging Microwave Radiometer Mission (CIMR) will focus respectively on sea-ice thickness, snow, ice sheets and glaciers (CRISTAL), and on a variety of sea-related parameters such as temperature and salinity (CIMR). These missions will provide a crucial contribution to environmental and climate monitoring; they are not expected to be routinely employed in action against environmental crimes but may provide supporting information on water levels (CRISTAL) and vegetation indices (CIMR).



Wildfires in Portugal. Contains modified Copernicus Sentinel data (2025), processed by ESA.

GENERAL ANALISYS

2. EO AND ENVIRONMENTAL CRIME LEGISLATION

This section focuses on the interaction between legislation adopted in the global fight against environmental crimes, and the use of EO. It aims at understanding how such legislation has recently evolved, and if it is already effective to maximise the contribution of EO in environmental enforcement. This section concentrates on three different levels: international treaties, EU legislation (as it is the most advanced from an environmental perspective) and national systems (from a general perspective, and including a few selected cases). It also dedicates specific attention to the issue of certification and the burden of proof.

2.1 INTRODUCTION

Lack of a duty to adopt EO

A formal obligation to use satellites in tackling environmental crimes is absent both at the international and the regional level, including in the EU where satellite applications are significantly embedded in the environmental crimes legislation. The lack of a legal duty upon states to do so makes satellite applications discretionary and contingent. Legal frameworks on environmental crimes have therefore integrated satellite applications very differently and to different extents at the international, EU and national levels, with notable divergence both within and among them. Few international treaties on environmental crimes make direct reference to the use of satellites as a relevant tool to detect, investigate and prosecute environmental offences. In addition, not only are international guidelines as to how satellites can be used to detect environmental crimes and as evidence in trials often lacking, they are currently not sufficiently used by international organisations or agencies as a way to overcome the absence of a legal duty concerning satellite application in environmental crimes.

Effectiveness and limitations of the EU framework

Conversely, satellites are strongly embedded in EU climate and environmental policies as well as in their environmental crimes legislation. The European Green Deal has further emphasised environmental protection as a key priority of the EU to be pursued also through the efficient and transversal use of satellite images and data, most emblematically in the EUDR. In the last few years, both the European Commission and the European Parliament have stressed the importance of integrating satellite applications in the EU's toolbox to prosecute illegal waste disposal, illegal logging and oil pollution, among other crimes (European Commission 2021b, European Parliament 2024). Yet, the EU's environmental efforts are weakened by the fact that the revised EU Environmental Crimes Directive – the key piece of legislation providing for the definition, sanctioning and prosecution of environmental crimes in the EU – does not include any reference to satellites (European Parliament and Council of the EU 2024a), despite encouraging the use of proportionate investigative tools, and despite the Commission's frequent mention of EO as a key instrument Whereas the international and EU levels aim to provide for consistent and common standards of satellite application in the context of environmental crimes, fragmentation persists at the national level in terms of, among others, satellites' integration, legal frameworks, legal standards and systems of proof. Partially, such divergences stem from pre-existing fragmentations concerning how domestic legal orders conceive and prosecute environmental crimes. The legal framework endorsed by European states has thus relevant consequences for satellite applications in tackling environmental crimes.

Similarities and differences with the past

It is finally worth noting that, while significant changes have taken place in relation to operational applications, uses in court have not evolved significantly in the past ten to 15 years. Comparing the results of this research to the *Evidence from Space* report that the London Institute of Space Policy and Law realised for ESA in 2012 (Kay et al. 2012), it appears that in the past 14 years the use of EO in court has little changed, since it already faced few obstacles: acceptability of data was already common in courts at the time of the research, certification was relevant and not an obstacle (similarly to nowadays, see the section on **Certification of satellite data**). However, fears that issues over privacy and unwarranted searches would arise (as highlighted in pages 41 and 171 of the *Evidence from Space* study) did not materialise.

2.1.1 National institutional frameworks: Law enforcement authorities

The legal frameworks that countries use to fight environmental crimes at the national level differ widely, as they could be either purely grounded in criminal law or administrative law, or could be the result of a different combination of the two. The type of legal framework endorsed depends on a country's legal traditions and on how supranational arrangements are transposed at the domestic level.

Emblematically, in many countries worldwide, criminal law has higher evidence requirements and a more stringent system of proof, in addition to limited or no criminal prosecutors and judges specialising in environmental matters (Colantoni et al. 2022a). These shortcomings discourage the efficient prosecution of environmental crimes through criminal law. Moreover, in several countries, criminal courts are congested, prison sentences are often suspended or rarely applied (such as in Finland) and environmental offences tend to be decriminalised (such as in the case of Poland) (Colantoni et al. 2022a).

The combination of these factors leads many countries to rely on administrative law to ensure more effective enforcement. In addition, environmental crimes are usually seen as a form of economic crime, on which the administrative apparatus has more experience and expertise. This is the case for many African and Asian states, which have acknowledged the severe impact of illegal fishing, yet several do not see it as a criminal offence, but rather as a fisheries management concern for which low and administrative penalties are foreseen (UNODC 2016). In administrative law, the standard of proof required is lower than under criminal law, which in turn facilitates the use of satellite data as evidence. Administrative law does not require evidence of the offender's liability. Yet, illegal activities against the environment addressed by administrative law often result in an economic fine without proper proceeding. Punishing environmental crimes solely through administrative law risks overlooking the severity of the misconduct at stake and undermining the efficacy of law as a deterrent. To address this tension between criminal and administrative law, the international community has tried to codify environmental protection within a criminal framework. The latest piece of legislation on environmental crimes is the first International Convention on the Protection of the Environment through Criminal Law, adopted by the Council of Europe in May 2025. However, despite the legislative progress, the document did not clarify the use of satellites, as it makes no explicit mention of remote sensing or satellite applications (Committee of Ministers 2025).

All in all, a sapient combination of criminal and administrative law is reportedly the best approach to improve the level of enforcement, a model already in use in some jurisdictions, including Finland and Brazil (Colantoni et al. 2022a, Tacconi et al. 2019). The precondition to do so is the existence of clear guidelines defining their interaction with existing sanctioning systems in addition to understandable definitions and distinct boundaries between administrative and criminal regimes, which are often lacking (Colantoni et al. 2022a, Tacconi et al. 2019).

Finally, another relevant element to take into account to evaluate the possibility for satellites to be integrated into legislation lies in the legal tradition (common law versus civil law) of the state concerned (see following section, **Legal systems**).

2.2 LEGAL SYSTEMS

Where satellites are used, national practices vary enormously especially according to the framework, administrative and/or criminal, to prosecute environmental crimes, but also due to 1) the different legal system (civil law versus common law countries); and 2) the authority that is mandated to tackle environmental offences (Colantoni et al. 2022).

Uses in civil and in common law

Although the demarcation between civil law and common law countries has softened over time, it is still relevant to mention. Traditionally, these legal systems differ in the sources of law and the role played by the judiciary in the law-making process. With reference to environmental crime enforcement, civil law countries traditionally adhere to formal rules of proof requiring multiple pieces of evidence to corroborate an environmental offence, in contrast with common law countries. In both Belgium and Germany, for instance, criminal courts can consider any form of evidence in trial. Hence, satellites are, in principle, eligible as proof of a criminal offence and it is up to the respective courts to decide on admissibility and reliability of the data as part of their assessment. In particular, judges need to assess the authenticity of the data, their quality and accuracy, and link the findings of satellite data with the facts and the liability of the perpetrator. However, both countries need other forms of evidence beyond satellite images to establish culpability, including direct observations. In other words, in civil law countries, an offence for environmental crimes cannot be based solely on proof stemming from satellite data. For example, the German federal police and coastguard use satellite images generated through Copernicus to assist in shipbreaking investigations falling under MARPOL (International Convention for the Prevention of Pollution from Ships). In those cases where satellite images were combined with open-source information, they triggered the initiation of 60 investigations and were used as evidence in court (Isarin et al. 2024). The legal tradition behind civil law and common law countries has evolved over time, smoothing the original differences. Nowadays, also common law countries, such as Australia, may need further proofs beyond satellite images in order to substantiate the existence of an environmental crime because of the difficulty for the satellite data to perfectly match judicial requirements. Similar is the case of South Africa. In the context of illegal fishing, for instance, there is currently no legal case where this crime was proven using solely automatic identification systems, whose receivers have been placed on low-earth orbit satellites. Yet, they have been successfully used as the sole piece of evidence for illegal fishing activity in proceedings that have less strict evidentiary requirements, such as in out-of-court settlements (Stop Illegal Fishing 2018).

Similarly, although Mexico (a civil law country) and the US (a common law country) traditionally respond to different legal systems, an in-depth look at the modern environmental enforcement processes in these two countries shows that they are very similar, and that the differing legal traditions have little impact on their respective enforcement effectiveness (Sinnott 1999).

2.3 FOCUS ON JUDGES AND PROSECUTORS

Different roles of judges and prosecutors across countries

In several countries, environmental crimes are investigated by specialised environmental inspection services. France, Luxembourg, Portugal, the Netherlands, Poland and Spain have specialised environmental inspectorates that are empowered to detect infringements of environmental law. In Norway, the National Authority for Investigation and Prosecution of Economic and Environmental Crime is the institution that both investigates and prosecutes the most complex cases on environmental crimes, which are also of particular public interest (Lavrysen 2006). In Brazil, IBAMA is the key federal environmental law enforcement agency, which tackles illegal deforestation by exercising the power of environmental police and carrying out actions related to environmental monitoring, control and law enforcement. In 2007, a new agency was funded, the Chico Mendes Institute for Biodiversity Conservation, responsible for forest law enforcement within federal protected areas in Brazil.

In certain jurisdictions, environmental prosecutors may not only discretionally decide whether to prosecute environmental crimes, but also whether to use satellites to collect data concerning a potential offence: this is the case in Belgium, where prosecutors seem to act against environmental offences reported to them in a very limited number of cases (8 per cent of instances) and not to use satellites systemically because of financial and technical challenges (Interview 14).

Conservatism of judges

In other cases, institutional resistance by judges to satellite applications is detectable. In Indonesia, for instance, "conservatism" among the judiciary has been observed in face of advanced and complicated scientific knowledge (Interview 15). Indonesian judges usually rely on expert testimony to interpret scientific evidence in environmental cases, as only a few judges are trained in environmental matters (Astuti and Fatimah 2024). The judiciary's limited understanding of scientific knowledge may hinder its efficacy in decision making. In addition, judges who are unfamiliar with satellite applications are sometimes reluctant to accept the innovative evidence of satellite imagery, thus further undermining the chance of sanctioning environmental offences.

2.4 INTERNATIONAL TREATIES

Treaties with and without an EO focus

There seems to be no consistent trend at the international level concerning the rising or decreasing regulation of satellites in the context of environmental crimes over time. However, four categories can be spotted when it comes to the application of satellites in international treaties concerning environmental crimes: 1) treaties which do not mention EO at all (such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora – CITES), the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes, or the Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC); 2) treaties which refer to EO only in monitoring programmes, which fall outside the scope of the present report, as in the case of the Bonn Convention on Migratory Species and the related Convention on Migratory Species' International Light Pollution Guidelines for Migratory Species (CMS, 2024); and 3) treaties which do not expressly refer to EO as part of their legal text, but mention it in related guidelines, programmes or plans of action. This is the case for the Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona Convention), whose legal text does not expressly mention satellites, but whose Mediterranean Strategy for the Prevention of, and Response to, Marine Pollution from Ships (2022–2031) and its action plan do refer to the use of satellite imaging to, among others, deter and detect illicit discharges and emissions from ships. In particular, the use of data and images from EO satellites (CleanSeaNet and Copernicus) is encouraged[28]. In addition, international organisations, such as UNODC and the Food and Agriculture Organization (FAO), have recommended, although in superficial and general terms, the use of satellites in monitoring, control and surveillance measures to combat fishery crime (UNODC 2023, FAO 2021, FAO 2024). A final category, 4) comprises treaties which, as part of their legal provisions, expressly mention satellites to fight environmental crimes. This last category is described in the section below.

2.4.1 International treaties expressly mentioning satellites

Among the list of agreed prevention actions to be undertaken by signatory states, the Bonn Agreement for Co-Operation in Dealing with Pollution of the North Sea by Oil and Other Harmful Substances includes the execution of aerial and satellite surveillance operations to detect, investigate, gather evidence and monitor oil spills and spillages of other harmful substances. In addition, by cooperating with the European Maritime Safety Agency (EMSA), the Bonn Agreement aims to make better use of satellite imagery to establish a harmonised system throughout the Greater North Sea to improve detection of pollution incidents. Finally, the Bonn Agreement Strategy Action Plan 2019–2025 envisages the coordination of aerial and satellite surveillance to detect threats of marine and air pollution (European Commission 2019).

The MARPOL Convention

MARPOL is the international environmental crime convention that most embeds the use of satellites as part of its legal obligations. Under MARPOL, signatory states are committed to cooperate in the detection of violations and the enforcement of the provisions set out by the Convention by using "all appropriate and practicable measures of detection and environmental monitoring, adequate procedures for reporting and accumulation of evidence". State practice has shown that satellites and satellite data are included among the appropriate and practicable measures, and have already been used to build a case for breach of provisions under MARPOL Annex I, II and V in the North Sea (Van Roy et al. 2024). Such attempts, however, have led to disappointing results in the North Sea Basin. For instance, no prosecution against pollution caused by oil spills from ships in the North Sea has yet been based on satellite images in Belgium and in the Ne-

28. REMPEC website : Mediterranean Strategy (2022-2031).

therlands (Van Roy et al. 2024)[29]. Beyond the EU, the Song San case involving Singapore emblematically shows the relevance and the untapped potential of satellites in prosecuting MARPOL violations in judicial proceedings (Oei 1999). In 1997 a Singaporean oil tanker, Song San, was accused of illegally discharging oil in Singaporean waters, causing severe marine pollution also to the adjacent coastline. The positive outcome of the case was also made possible by the use of satellite images, which were submitted to the court as evidence together with oil samples. In this peculiar case, the court recognised the effectiveness of technology to conduct surveillance and enforcement of laws on marine pollution. Yet, in general, several (capacity, financial, political, legal and judicial) challenges still hinder the adoption of satellite technologies and their use as proof of environmental offence in court (see **Obstacles – Judicial obstacles**) (Eurojust 2021).

2.5 EU LEGISLATION

The Union's attention towards environmental protection and the cross-cutting use of satellites in relevant EU policies, from space surveillance to environmental monitoring, has considerably increased over time. This evolution is particularly tangible in the growing number of EU environmental criminal laws explicitly relying on satellite data and images over the last decades.

2.5.1 International treaties expressly mentioning satellites

First integration of space into EU legislation

Satellites were first integrated into the EU's policy on space back in the 1970s, in particular thanks to the work of ESA. It is in the first decade of the 2000s that satellites started to be superficially mentioned in relevant provisions on environmental crimes. For instance, Regulation 2244/2003, repealed by Regulation 1224/2009, laid down detailed provisions regarding satellite-based Vessel Monitoring Systems and established common requirements for satellite-tracking devices on EU fishing vessels in order to properly detect, investigate and sanction illegal activities at sea (European Commission 2011). However, no information was provided as to how satellite data could be used as evidence of alleged violations in bringing related cases to courts. The 2009 Regulation was amended in 2023, yet details about the admissibility of satellite evidence in judicial proceedings are still lacking (European Parliament and Council of the EU 2023).

2.5.2 Satellites in the recent work of EU institutions on environmental crimes

By 2018, however, the Union had strengthened its awareness of the potential of

29. Yet, in the Netherlands, eight out of the nine cases using airborne observations of violations resulted in penalties with fines ranging between €15,000 and 20,000.

The 2018 Communication on environmental compliance and governance

satellites in prosecuting environmental crimes, as also demonstrated by the 2018 European Commission Communication on *EU Actions to Improve Environmental Compliance and Governance*, where the accessibility of EU-generated data sources, such as satellite imagery, is foreseen to enhance assurance of effective compliance (European Commission 2018). In 2021, the European Commission produced guidelines for combating environmental crimes and related infringements (European Commission 2021b). In this document, the Commission acknowledged the relevant role of Earth Observation and satellite tracking as visual evidence in criminal trials. On the one hand, the Commission noted that, because satellite data are constantly collected and stored for future use, they allow authorities to go back in time when investigating illegal activities – including illegal waste disposal, destruction of a protected habitat, or illegal logging – and establish a timeline for an infringement. On the other hand, it recognised that procedural challenges exist in the evidence-gathering stage of criminal proceedings.

The 2024 Directive on ship-sourced pollution

At the core of recent EU legislative efforts is the strengthening of maritime environmental enforcement. In April 2024, the European Parliament adopted the provisional agreement, adopted by the Council in November of the same year, on the revision of Directive 2005/35/EC on ship-sourced pollution and related penalties (European Parliament 2024), which has also been further strengthened by the new Environmental Crime Directive. The revised text will now include five references to satellites. Its aim is to, inter alia, enhance the information required for the effective implementation of this Directive, in particular as provided by CleanSeaNet, with a view to developing reliable methods of tracing polluting substances at sea. In addition, the agreement stresses that information relating to discharges reported by member states and by other Union maritime safety databases (i.e., SafeSeaNet and THETIS) should be integrated and disseminated to the national authorities involved in the enforcement chain to facilitate their timely response to such potential illegal discharges. Preamble 33 suggests reviewing MARPOL to also assess ways to improve satellite surveillance of lost containers, potentially including harmful substances.

EO for member state compliance

Finally, EU institutions are increasingly relying on satellites to detect and sanction EU member states' environmental offences. Emblematically, the European Parliament has accepted petitions to contrast illegal logging and the deforestation of virgin forests in Romania (Kindji 2021). Petitioners denounced the massive increase of illegal logging due to the discontinuation of the forest surveillance system via satellite, as a result of political pressure. For its part, the European Commission launched an infringement procedure against Romania for breaches of EU environmental law in relation to forestry activities. Using satellite imagery, the Commission also found that protected forest habitats have been lost within protected Natura 2000 sites, a network of nature protection areas in the territory of the European Union, in breach of the EU Birds and Habitats Directives.

2.5.3 Satellites in the Union's recent legislation on environmental crimes

EO and Green Deal legislation

The first von der Leyen Commission, coinciding with the ascent of the European Green Deal, created momentum towards a more efficient prevention and prosecution of environmental crimes also through the use of satellites. Among other provisions, the EUDR requires agricultural commodity producers and manufacturers to present satellite-based proof that their products are deforestation-free. The assessment will be done by collecting the geolocation coordinates of a plot of land via mobile phones thanks to Global Navigation Satellite System (GNSS) devices, in addition to optical satellites (Sentinel-2) to be complemented with SAR data (Sentinel-1), and EOS SAT-1. Moreover, the Nature Restoration Regulation requires EU member states to maximise the access and use of data and services from remote sensing, Copernicus satellite services and products, geographic information systems, in situ sensors and devices, data analysis and processing, and AI to increase the speed, effectiveness and coherence of multiple monitoring and reporting processes (European Parliament and Council of the EU 2024b). Finally, the New EU Forest Strategy for 2030 encourages states to leverage Galileo and Copernicus services to improve strategic forest monitoring, reporting and data collection (European Commission 2021c). An even more extensive mention of the use of Copernicus data was made in the Commission proposal *On a Monitoring Framework for Resilient European Forests* (European Commission 2023). In September 2025, the law was voted down by a coalition of centre-right and far-right groups who argued against unnecessary bureaucracy and high costs (Fern, 2025).

The new envicrime Directive and EO - a missed chance

Such renewed attention towards the integration of satellites in environmental crimes legislation makes it even more surprising that the revised EU environmental crime directive, namely the key piece of EU legislation concerning the prevention and sanctioning of environmental crimes and the prosecution of their perpetrators, makes no reference at all to the use of satellites. This is a missed opportunity not only because it neglects the relevant role played by satellites in this field, but also because it fails to define the unique role of satellites in the different phases of criminal proceedings, from the detection of a potential violation by prosecutors to using satellite data as admissible evidence in trials.

2.5.4 The EU's increasing financial investments in satellites over time

New EU investments in EO

The relevance of satellites for the EU is also demonstrated by the increasing investments that the Union has made in this field, particularly if we look at the skyrocketing budget used to finance the development of Copernicus, the EO flagship component of the EU's Space Programme. From 2007 to 2013, most of the 6.7 billion euros allocated to the development and implementation of the space infrastructure were dedicated to Copernicus[30]. Afterwards, the 2014–2020 multiannual financial framework adopted by the Commission created a specific budget line for the Copernicus programme, further expanding its financial scope to 4.3 billion euros (European Parliament and Council of the EU 2014). In addition, Horizon 2020 offers additional funds to research and development activities in the field of Earth Observation. Further, as part of the new EU Space Programme for the period 2021–2027, proposed by the Commission in 2018 and adopted in 2021, EU institutions aim to safeguard the continuity and evolution of the EU's global and regional satellite navigation systems (Galileo and EGNOS – the European Geostationary Navigation Overlay Service) as well as Copernicus. Under this arrangement, the budget for Galileo and EGNOS further increases by 9.02 billion euros and by 5.42 billion euros for Copernicus (European Parliament and Council of the EU 2021).

Competition with the US and China

Yet, the EU lags behind in the space competition compared to the US and China. In 2024, the US had the largest global space budget (over 60 per cent of the world's total), while China had reached 15 per cent through ambitious long-term programmes in both civil and defence sectors. Both countries surpass the space budget allocated by the EU, which still accounts for just 10 per cent of the world's total (ESA 2025). Data collected by ESA on space activity by major players between 2015 and 2024 reveal a wide disproportion in terms of funding gaps and human spaceflight, whereby the US, China and Russia account respectively for 34, 30 and 21 per cent of the total mass launched for government programmes, while Europe accounts only for 7 per cent (ESA 2025). In addition, the EU is investing far less than the US in satellite research and development (investment in this area is one-third that of the US). What is more, China is achieving impressive technological results, such as the development of a new satellite mega-constellation comprising 14,000 satellites, which doubles the American Starlink (whose mega-constellation contains 7,000 satellites at low-earth orbit) (Goldstein 2025).

2.6 DOMESTIC FRAMEWORKS

There is no uniform standard for regulating the use of satellites as evidence of an environmental offence in trials at the national level, as countries worldwide have

30. In greater detail, 85 per cent of the total or 1.4 billion euros. See: Darnis et al. (2016)

legislated very differently on the topic. Differences pertain not only to the issue of the use of the satellite data in trials, but also to the requirement for such data to be certified to be admissible as legal proof.

2.6.1 Domestic law on environmental crimes with direct reference to satellites

There are states whose domestic law on environmental crimes expressly mentions the use of satellites. Such is the case for Morocco's 2014 law to prevent and fight illegal, unreported and unregulated fishing (IUUF) crimes, which explicitly refers to the use of satellite surveillance to detect and prevent this crime. In other cases, such as in the US and Peru, domestic law expressly mentions the use of satellites in tackling environmental crimes but requires satellite data to be evaluated by recognised experts in order to be admissible in criminal proceedings (see Certification of satellite data) (Dighe et al. 2012). Then there are countries where satellites are required in order to prove an environmental offence, but need to be supplemented with other evidence. This is the case in Indonesia, whose domestic law on forest fires demands both satellite imagery and field verification through the analysis of soil samples taken from burned land and examined by an accredited laboratory (Resosudarmo 2023).

2.6.2 Domestic law on environmental crimes with no direct reference to satellites

Some countries, like France, do not have specific legislation regulating the use of satellites in trials, but judges have confirmed that satellite data can be admitted as evidence for the conviction of environmental offences, although in a very limited number of cases[31]. Similarly, Belgium does not have a specific provision regulating the use of satellites in cases concerning environmental crimes. Yet, the system of proof that applies in criminal proceedings is free, meaning that proof may be provided by any means (Billiet 2012). Thus, satellite images are, in principle, admissible as evidence, and it is up to the court to assess the reliability and relevance of such proof on a case-by-case basis.

2.6.3 Challenged application of satellites

Finally, there are countries that have regulated the use of satellite images to fight environmental crimes, but where such legislation is porous, such as Romania and Ghana. In 2014, Romania first introduced a mandatory digital tracking system for trucks transporting wood, which allows for meticulous tracking of the number of cut trees, their pickup and delivery locations, as well as the registration of truck drivers. However, this measure turned out to be insufficient to avoid illegal logging because truck drivers would use fake GPS loading points (EIA 2015). As

31. These are the TRAQUAIR case of 1995 and the SALAMINA case of 1996 concerning oil pollution offenders in France (Cedre 2007).

for Ghana, in 2010 it adopted Regulation 42, which mandates all Ghanaian flagged vessels to install onboard vessel monitoring systems before they can engage in any form of fishing activity (Yakubu 2022). This relevant attempt to tackle fishery crime through satellites has so far been undermined by the lack of legislation enabling the prosecution of maritime crimes in Ghana.

2.7 CERTIFICATION OF SATELLITE DATA

All images and data that are used in court as evidence may require a certification process to guarantee their authenticity, which may be compulsory or recommended, and more or less complex depending on the national judicial system.

Certification for satellite images is however particularly relevant, since they are the end products of complex data supply chains, whereby vast amounts of data are collected, processed and presented in digital formats for consumption and/or analysis. From the perspective of admissibility, a longer supply chain increases potential sources of error or manipulation; while this is practically impossible when dealing with well-structured sources, such as Copernicus or USGS, this issue could become relevant as the number of providers multiplies. In this sense, certification of the data could be a solution to guarantee the reliability of the information used as evidence.

2.7.1 Role of certification

Certification processes

The certifiability of the data by an independent authority aims to ensure that the results of the method cannot be falsified. Digital data are especially subject to manipulation. For instance, data can be manipulated to make them convertible into other suitable formats, such as printouts, or to intervene on the colours of the image to make it clearer. If a litigating party has made a manipulation, its legitimacy will be assessed by confronting it with the original certified image. In Peru, for instance, environmental prosecutors have official laboratories to validate satellite data, where experts undertake specific training on satellite monitoring and imagery use and provide consultation on the validity of satellite data before it can be admitted to court (Interview 4). In the EU, the verifiability, traceability and interpretation of satellite images or data are a persistent concern (EARSC 2021). According to the European Association of Remote Sensing Companies, potential solutions to overcome these challenges include the appointment of experts by the court or by the parties concerned, as well as the implementation of a certification system, which would be responsible for the certification and standardisation of data, run by a body (or bodies) at the national or international level (EARSC 2021). Certification also ensures that all parties in the trial have access to certified satellite data provided by a dedicated authority, which could be used in court in a contradictory procedure (ESPI 2010).

2.7.2 Traceability of the EO supply chain

Traceability of data

The ability to document and audit every step of the data production chain, from raw sensor output to final processed product, is of the utmost importance for the certification process. This maps directly onto evidentiary concerns about the chain of custody and the integrity of scientific evidence, since any break in traceability undermines the ability to verify the data's accuracy before a court. A positive signal in this domain is the establishment of traceability chains, which are being developed for climate change services in the framework of Copernicus[32]. The traceability service allows for the complete tracing of a data product's integrity from its origin to its download. It allows users to verify that the data are original and untampered with. In legal proceedings, this process of establishing a reliable traceability system for the entirety of the EO supply chain could signal a first mirroring of the doctrine of chain of custody – the requirement that evidence be accounted for at every stage of its handling to ensure it has not been tampered with, corrupted or misrepresented. While this is a positive step, there are still no international standards that provide an encompassing accepted global standard for traceability.

2.7.3 Examples of malicious manipulation

An additional complication is the rise of AI-generated synthetic images that could impact the reliability of all imagery – satellite data included. Synthetic satellite images are indeed a growing issue in this sector, and consist of artificially generated images created by algorithms and computational techniques (Toscano 2025). Such process make it possible to create images of realistic appearance that, in many cases, are indistinguishable from an authentic image to the naked eye. This issue is already materialising, as happened in 2025 when deepfakes were published to exaggerate the effect of military strikes in conflicts, a practice that could soon take place in observing environmental crimes as well (Undseth and Jolly 2026). Such practices could result in detrimental consequences when combating environmental crimes. The size of glaciers and deforestation, or emissions, could be altered, resulting in delayed measures against climate change and environmental policies, a consolidated practice known as deepfake geography (Eckart 2021).

Additionally, at a more fundamental level, the issue of spoofing threatens the integrity of the whole supply chain. Spoofing is the act of forging or falsifying data or

32. Copernicus Data Space Ecosystem website: Traceability service.

signals to deceive a system into accepting them as legitimate. Researchers at Oxford University have, in fact, analysed NASA's live forest detection system and demonstrated that an attacker can achieve arbitrary manipulation of fire detection to trigger false emergency responses or mislead crisis analysis (Salkield et al. 2023). A first-step voluntary certification that media outlets have started using to fend off AI fakes is, for example, self-reporting and explaining how they verified the image, providing the link to an official clarification (Africk 2025).

2.7.4 Certification in focus: The case of the US

Role of USGS/EROS

Some systems of certification already exist in the US. Among others, the Department of Interior's United States Geological Survey at the Earth Resources Observation and Science Data Center (USGS/EROS) collects and uses data from remote sensing satellites and other sources in order to provide information regarding Earth's changing land surfaces. The centre also certifies copies of the images for litigation purposes. The certification procedure has changed over time. In the 1970s, USGS/EROS used to certify photographic prints. The certification process for photographic images involved the submission of a certification request, on which a USGS seal was attached together with a signature that provided the source or authenticity of the data (EROS, 2018). Certified copies of images were routinely accepted as evidence by courts based on the process used by USGS/EROS to collect, store and reproduce the data. Yet, a witness was rarely available to testify that the photographic representation was a fair and accurate depiction of the scene, as national law demanded.

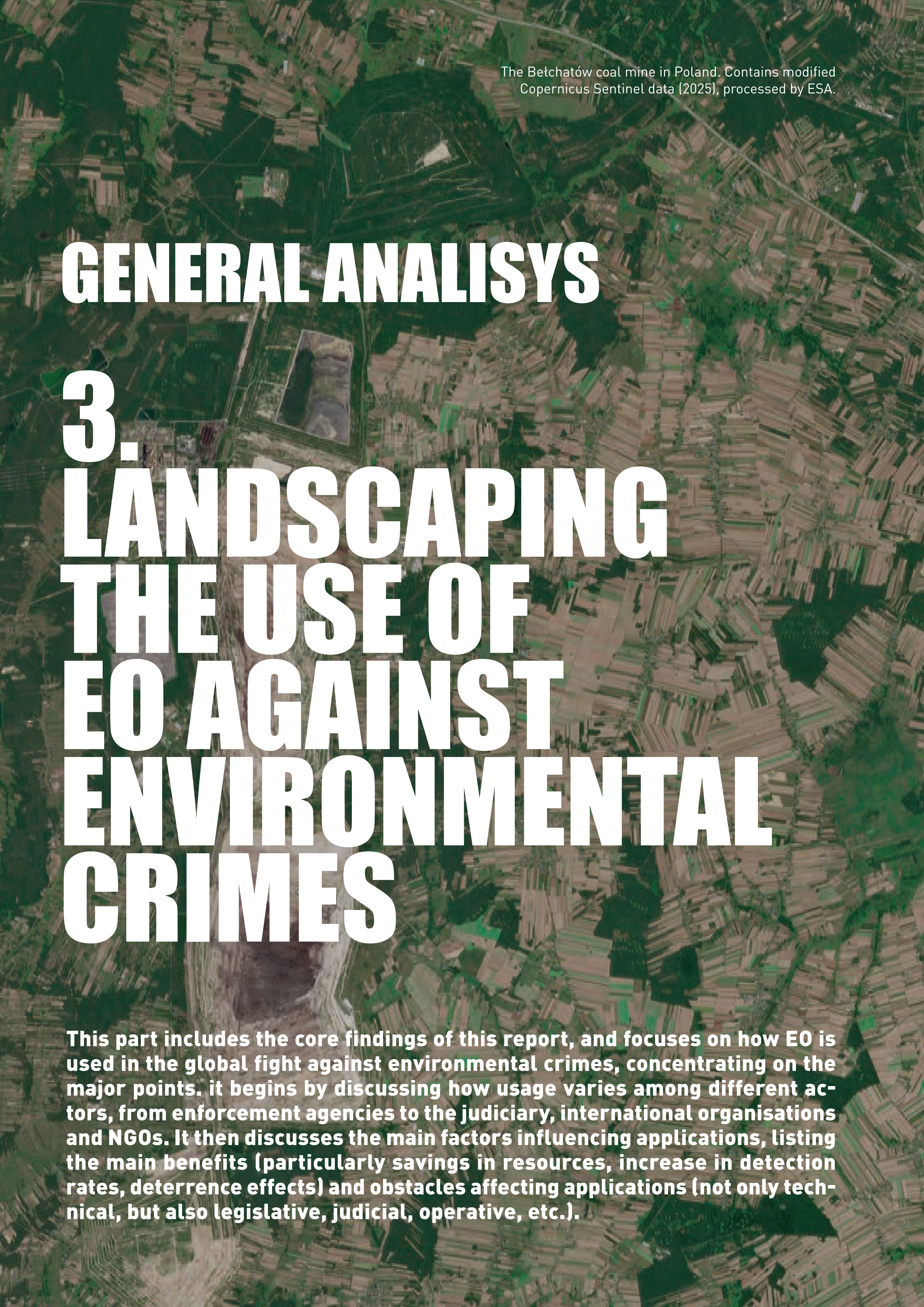
After a study conducted by USGS/EROS and the National Center for Remote Sensing, Air, and Space Law at the University of Mississippi, a new certification process was developed in order to transpose certified digital data onto CDs or DVDs instead of prints[33]. According to this new model, USGS/EROS downloads satellite images in digital format, and then transfers them to the EROS archive in South Dakota, where they are stored in computer databases. The validity of digitally certified images is ensured through a unique product number associated with each certification request, which is also printed on the CD/DVD, embedded in the digital data and preserved in USGS/EROS files. This procedure allows digitally certified satellite images to be used as evidence in court.

Other methodologies

Regardless of the modalities implemented to certify satellite images (traditional photographs or digital), US national law requires remote sensing data to be explained and interpreted via expert testimony in order to be admissible in criminal proceedings (Zhang et al. 2024). Indeed, expert witnesses who are familiar with the field and office procedures have always been employed to assess whether satellite images fairly and accurately depicted something relevant to the trial. In addition, experts certify that the satellite data have been collected and managed properly.

A final certification available in the US is that delivered by the National Centres for Environmental Information (NCEI) on weather reports. Indeed, NCEI provides official certification for data used in US courts as evidence that meets the authentication requirements for records[34]. NCEI allows certified data online for certification of weather records, as well as hard copies of Next Generation Radar (NEXRAD) Level II and Level III radar images for use in court.

33. According to US law, satellite images can be presented in the form of charts, summaries or calculations and allowed as evidence. See Rychalk et al. (2007).
34. National Centers for Environmental Information website: Data certification.



The Bełchatów coal mine in Poland. Contains modified Copernicus Sentinel data (2025), processed by ESA.

3. LANDSCAPING THE USE OF EO AGAINST ENVIRONMENTAL CRIMES

This part includes the core findings of this report, and focuses on how EO is used in the global fight against environmental crimes, concentrating on the major points. it begins by discussing how usage varies among different actors, from enforcement agencies to the judiciary, international organisations and NGOs. It then discusses the main factors influencing applications, listing the main benefits (particularly savings in resources, increase in detection rates, deterrence effects) and obstacles affecting applications (not only technical, but also legislative, judicial, operative, etc.).

3.1 INTRODUCTION

Considering the still-ongoing evolution of the sector, satellite applications against environmental crimes are particularly varied and multifaceted, as well as rapidly changing. Before illustrating the main areas of application, actors involved, benefits and obstacles, it is worth noting two main findings of this research.

More success on operative than judicial applications

First, satellite applications are more common and more successful on the operative, than on the prosecution and judicial sides. In other words, it is much more common to see civil society and enforcement agencies using satellite data, than to find court cases where prosecutors have employed them as evidence (Interviews 11 and 31). This outcome is due to a variety of causes, discussed in detail in the **Main Obstacles** section; above all, legislative frameworks and judicial systems have been slow in integrating satellite applications (especially compared to the speed of technology development), while national institutions are still lacking the specialisation and resources to properly use them. On the other hand, despite leading to only a few court cases, the monitoring of farmland or forests has proved to have a relevant deterrent effect on offenders (Interviews 11, 36 and 37), and has significantly eased the work of enforcement agencies, particularly on vast or inaccessible territories, such as the Indonesian archipelago or the Amazon.

As a consequence, most uses are still largely related to monitoring for offenses, early inputs to investigations and deterrence. It is indeed still uncommon to find satellite imagery used as evidence in court, although this is changing and the situation varies from country to country; while this is valid for most European countries, in states with a more consolidated use of EO it is relatively common to see satellite imagery in court (this is for instance the case in Brazil, Indonesia and Costa Rica).

Another consequence is that EO analysis is done in many cases outside enforcement agencies, and applications are developed mostly by NGOs and international organisations (although sometimes with a direct involvement of enforcement agencies). There are a number of reasons for this: the lack of resources, high turnover and relatively low technological awareness above all have limited the ability of enforcement agencies to develop internal EO capabilities, which are as a consequence either sourced outside, or within national institutions (such as Vietnam's Remote Sensing Institute) or specialised units.

A corollary of this finding is that there is a remarkable difference between targeted uses, and the role of platforms. This research has indeed identified two frequent applications of EO against environmental crimes: usage specifically adopted for relevant cases, developed by EO experts, and the use of platforms to support monitoring and investigations, usually by non-expert users. Applications developed specifically for cases are much more accurate, flexible and reveal more detail (see for instance **Case 1** or **Case 9**). They are however not easily accessible for all institutions, since they require a robust access to data and, above all, a dedicated expertise which is not easily available to enforcement agencies. Platforms such as Global Nature Watch are instead very easy to use and to integrate in a variety of activities (for instance through the "alert" function that gives constant updates about canopy disturbances on areas the user can autonomously select). On the other hand, these platforms often lack the flexibility, the accuracy and the endowment of information that is required in investigations, and their use is thus still limited.

Need for combining EO with other toolsCertification processes

Finally, while many in the environmental action community still consider EO a stand-alone tool, integration with other technologies, among different satellite data and with other investigative tools is crucial. In fact, the use of multiple data sources brings remarkable results in most cases; a central issue in expanding the use of EO against environmental crimes would be to develop platforms and methodologies to integrate them with other kinds of open-source intelligence (OSINT) or human intelligence (HUMINT), as well as other technologies. Additionally, as it is well known in the EO community, satellite data show correlation, but not causation: in this sense, in most cases satellite applications alone are not enough to prove guilt, and additional evidence is required in court.

Reasons for these two elements are varied, and discussed extensively in the **2.5 Obstacle**s section. Generally speaking, the number of environmental crime cases globally is usually low, particularly when compared to the number of offenses detected by enforcement agencies (Colantoni et al. 2022a). There are also some legal obstacles to using EO in court in some countries (see **Obstacles – Judicial obstacles and Certification of satellite data**). In several cases satellite data are employed in early stages of the investigations, but then as evidence is gathered on the ground, this is instead used in court.

3.2 MAIN ACTORS

In the fight against environmental crimes, the enforcement segment is where usable Earth Observation intelligence is applied in investigations or other enforcement action. This segment is represented by all authorities charged with environmental enforcement action, from police forces to environmental agencies, ministries and even customs and border control.

Although environmental investigations are led solely by police forces and prosecutors, there is a variety of other players who make significant contributions to action against environmental crimes, and all these players use satellite data in a different way. Civil society often provides crucial intelligence to enforcement agencies, while international organisations frequently support judges, prosecutors and police officers through capacity building, or help with advanced analysis of evidence. This report analyses in depth the role of seven main categories of users: law enforcement agencies (LEAs), prosecutors, judges, civil society (national and international), civil society (local), international organisations and the private sector.

3.2.1 Law enforcement agencies (LEAs)

The core of environmental enforcement

LEAs include national police forces, as well as agencies with specific competencies, such as customs, and environmental inspectorates. This category comprises entities dealing with criminal and administrative law.

Enforcement agencies are central to combating environmental crimes, being the sole organisations capable of carrying out investigations in most nations, although prosecutors lead them in certain countries and civil society can be involved in others (Colantoni et al. 2022a). As a consequence, they should be the main users of satellite applications against environmental crimes, as they would be able to apply them directly in enforcement action. This is, however, frequently not the case, since these agencies are limited by a series of obstacles (discussed specifically in 2.5 Main Obstacles), such as the high turnover of officers and the limited resources for capacity building and GIS training. While in some cases LEAs directly employ satellite applications in their work (particularly for administrative cases), in several others they receive and verify the analysis already produced by partners such as international organisations and civil society (which could be the identification of suspicious vessels, of potential areas of illegal mining, spotting canopy disturbance in forests, etc.).

3.2.2 Prosecutors

Investigations and validations

Prosecutors represent another key player in action against environmental crimes. Their level of involvement changes from country to country; in some, such as South Korea, prosecutors can lead investigations. In contrast, in others, as in Spain, they work closely with LEAs, while in only a few cases, their investigative role is very limited, as in Canada (Choe 2018). Prosecutors are known to actively use satellites against environmental crimes, similarly to

LEAs (Interview 11), although with the same limitations in terms of low specialisation and awareness on the availability of data and applications. Additionally, depending on the legislation, satellite evidence needs to be validated by prosecutors (who in turn use certified experts or laboratories) (Interview 11).

3.2.3 Judges

Judges do not represent, in most cases, active users of satellite data, since investigations are done by prosecutors and by police forces, which also perform the analysis (together with civil society and international organisations). Judges however still play a significant role in satellite applications against environmental crimes; they evaluate the admissibility of satellite evidence and, more generally, they have the ability to decide whether a case is worth pursuing, and thus whether to authorise the use of advanced forensic instruments (Colantoni et al. 2022a). Judges with a better environmental expertise will thus tend to be more accepting of the use of satellite data in courts, and indeed their low level of specialisation (in the EU and globally) represents a major hindrance to their acceptance of such data (see **Obstacles – Judicial obstacles**) (Colantoni et al. 2022a).

3.2.4 Civil society

Civil society is one of the most important users of satellite applications, at different levels and in different ways. NGOs dealing with environmental crimes are usually divided (Colantoni et al. 2022a) between those with a national and international perspective (WWF, Greenpeace), and local organisations. The latter can be totally autonomous entities run by community members or, in some cases, territorial offices of national and international organisations. These two categories play different roles in action against environmental crimes, and this is clearly reflected in their use of satellites.

Civil society: National and international

Focus on platforms and larger projects

National and international organisations are usually focused on larger projects, which often involve the scanning of vast territories, or on the development of user-friendly platforms. This is for instance the case with the satellite analysis done by the Monitoring of the Andes Amazon Program (MAAP) on illegal mining in Ecuador in 2024 (MAAP 2024), or the work of WRI, the creator of Global Forest Watch. Even non-profit entities outside the environmental sector are making a relevant contribution: Ai2, an AI research institute launched in 2014, is the key player behind the Skylight and Earth Ranger platforms, for instance[35].

Civil society: local

Local organisations are also users of satellite data, although often in a different

35. See Ai2 website.

fashion. The applications often refer to individual cases in the territory where the NGO is located, and tend to be focused on the topics the entity usually deals with – particularly deforestation, landscape change, exploitation of natural resources and, to some extent, pollution. The analysis is usually conducted internally by a GIS expert belonging to or affiliated with the organisation, or by a member who has received training on the use of platforms and basic analysis. Although it is not particularly common to find such expertise in local NGOs, this is more frequent in cases where they have been exposed to crimes where the satellite provides particularly useful evidence: this is, for instance, the case for local NGOs working on deforestation in Brazil and Indonesia (Colantoni and Sangiorgio 2024b).

3.2.5 International organisations

International organisations are also another major user of satellite data against environmental crimes. This category refers to a variety of entities, dealing with different issues and using different tools; among the most relevant, UNODC has extensive expertise in satellite analysis, and is particularly concentrated on deforestation, illegal mining as well as sea pollution and fishery crime (the latter being the focus of its Global Maritime Crime Programme, GMCP). Interpol also has relevant expertise (particularly on mining and deforestation). These organisations play a role that to some extent is similar to that of civil society, although with a few differences; in most cases, international organisations either act as consultant for national enforcement agencies, providing the analysis and in some cases the satellite data as well (this is particularly true of Interpol) (Interview 8), or cooperate with them to launch major initiatives, often with a transnational focus. In 2018, the most important international organisations with a mandate on environmental crimes, namely Interpol and UNODC, launched a joint project called LEAP (Law Enforcement Assistance Programme) to support law enforcement agencies in Latin America, Asia and the Pacific to tackle illegal deforestation and associated crimes. Since then, LEAP has assisted participating countries to detect, investigate and prevent forestry crime more effectively. Interpol and UNODC provide member states access to satellite imagery supplied by private companies or foreign space agencies, making them able to detect deforestation hotspots within and across national borders and beyond their national capabilities. In 2019 alone, Interpol-related law enforcement operations targeting illegal logging and wildlife crime led to approximately 20,000 seizures and more than 600 arrests (Interpol 2021).

In some cases, also other national institutions join these partnerships, as happened in 2022 for USGS, which started providing EO to UN agencies to counteract global illegal mining (Lazenby 2022). The development of foundational platforms often sees the direct involvement of these organisations (UNODC promotes the use of Skylight, for instance), which offer guidance and technical support[36].

3.2.6 Private companies

Involvement of private players

As a consequence of the growing involvement of private players in EO, companies are now also starting to play a role in the use of satellite data against environmental crimes. This contribution is still in its early stages, as most of these businesses are focused on commercial support to sectors such as mining and agriculture (which is much more financially rewarding than supporting law enforcement). A few companies are, however also offering EO analytical platforms, which can also be applied to environmental crimes; this is for instance the case for EOLAS, which is working on wildlife conflict and poaching (see **Case 8**)[37]. Private companies are however much more often requested by NGOs and other players as providers of imagery that programmes such as Copernicus and Landsat cannot supply (particularly high resolution imagery); however, most of these data providers also offer analytical tools and platforms that can be applied to environmental offenses as well, as in the case of Planet[38]. Enforcement agencies, international organisations and even civil society have used data and analytical tools provided by private players; for example, Global Witness commissioned the EO company Planet to scan the Kachin region in Myanmar for its investigation on illegal mining of rare earth elements (REEs) (Global Witness 2022).

3.2.7 Main factors influencing applications

The role of satellite applications in action against environmental crimes is very relevant and, in some sectors, even pivotal (as in the case of illegal logging or mining). However, it is still quite heterogeneous in terms of relevance and inherent features across areas of application, players and regions. This research has identified four main factors that determine the importance of satellite applications against environmental crimes: geography, sector, technological capacity and legislative frameworks (Interviews 11 and 31).

3.2.8 Geography

Large territories and EO

This variable can influence the use of satellites in both a positive and a negative way. Countries with large, uninhabited and/or hard to access territories tend to use EO more and earlier. They also tend to apply it to environmental crimes more widely than countries with a more accessible or anthropised landscape. Such early use has been for instance the case in Brazil, Indonesia and South Africa, which are in some cases more advanced in satellite applications than most European states, usually because satellites have represented a cheaper and quicker way to monitor complex territories since the 1990s, and have been thus integrated into policies and legislation since the early 2000s. This use has been reinforced also by the importance of the exploitation of natural resources and of agriculture in these countries: in countries like Brazil EO has been used for decades to plan land use and to monitor violations such as encroaching or violating concession boundaries.

Cloud cover and revisit frequency

The geography of a country can however represent an obstacle, mostly due to instances related to the weather or the latitude. The frequent cloud cover over the Amazon has represented for instance a significant impediment to the application of the DETER system in Brazil (Sales et al. 2022), particularly in northern areas where the cover is generally more persistent. While the use of Sentinel-1 SAR data (as part of ESA's Amazonas project) has significantly improved the situation (GIM International 2023), this still represents a significant limitation for the more available optical data.

3.2.9 Sector

The variety of environmental crimes means that some are a better fit with satellite applications because of features such as their impact on the landscape, structure of the supply chain, and criminal methodologies (Interview 8).

In general, satellite applications are more common for environmental offenses which are very visible either from optical imagery, such as in the case of logged areas, and to a lesser extent from multispectral imagery, such as illegal water extraction, or for which alternative tools for data gathering are more expensive (because of the size of the territory, its accessibility or security issues). This is the case for illegal logging and forest fires, illegal construction and most cases of illegal exploitation of natural resources On the other hand, satellite applications are less common for offenses whose detection requires a high revisit frequency or a high level of detail (which would significantly increase the cost of satellite data) or are simply complicated to detect (pesticide pollution, for instance). This is the case for the killing, destruction, possession or trade of protected wildlife and plant species, of illegal ship dismantling, and some cases of air, water and land pollution. The application in sectors such as fishery crime, waste trafficking and illegal waste disposal instead usually depends on the case – for waste trafficking, for instance, satellites are used to detect large illegal disposal sites (Fraternali et al. 2024), but their employment in other cases is still limited (Interview 12).

3.2.10 Technical capacity

The ability to access, analyse and integrate satellite data into environmental in-

36. UNODC website: Skylight-GMCP Partnership.
37. EOLAS website: About EOLAS Insight.
38. Planet website: Planet products.

vestigations is equally crucial for their employment, and is influenced by a series of factors: availability of data, expertise of the players involved and level of analysis required by the case.

Availability of data and analytical expertise

Availability of data is not an issue in some cases, thanks to the endowment of information provided by the Copernicus and Landsat platforms. However, in other cases investigations would also need higher resolution data (as it happens, for instance, with oil spills), which would in turn require significant economic resources (Interview 7). In still others, enforcement agencies or other users are simply not aware of the existence of free data and platforms, or of their actual capabilities (see **Main obstacles**) (Interview 33). The expertise of users is indeed related not only to their actual individual capacity to analyse the data, but also to their knowledge of AI, web platforms and other tools that can automate and perform processes that are otherwise very complicated (as in the case of the manual detection of oil spills in large ocean areas). However, even if tools such as Skylight can significantly reduce the expertise required, the identification of certain offenses may still require the involvement of GIS professionals (thus increasing costs and reach of satellite applications).

3.2.11 Legislative frameworks

Burden of proof, certification requirements and environmental legislation

Legislative frameworks can play a crucial role in spreading (or blocking) satellite use to counter environmental crimes. While this is discussed in detail in section EO and environmental crime legislation, there are a few enabling factors that are worth mentioning here: burden of proof, satellite certification requirements, familiarity with satellite applications and general strength of environmental legislation. Countries where courts require a higher burden of proof tend to reject satellite data more frequently as evidence (as in the case of France, for instance) (Colantoni et al. 2022a), while others require validation via expert testimony: while in some cases this is a relatively smooth process (e.g., Peru) (Interview 11), it conversely may be expensive and complicated in others (e.g., the US) (Zhang et al. 2024). If the country has already integrated the use of satellite imagery into other kinds of legislation, the consequent familiarity may also increase the general expertise of judges on the topic, and boost their acceptance of satellite evidence. Finally, legislative frameworks are very heterogeneous in terms of strength and attention to environmental offenses, across sectors and countries. This is also true for the EU which, despite the 2008 Environmental Crime Directive, and the significant amount of environmental legislation enacted in the past two decades at the Union level, still suffers from strong heterogeneity across national environmental frameworks. The 2024 Directive is however still being transposed by Member States, and its effects are yet to be seen. Stronger environmental legislation generally favours the integration of enforcement technologies, and is thus associated with a better employment of satellite data.

3.3 MAIN SECTORS OF APPLICATION

Satellite applications are effective against most environmental crimes, although with some exceptions and with some sectors benefitting from more consolidated uses. For instance, several instances of trafficking of waste, wildlife or of environmentally harmful substances, such as F-gases, are traded in small quantities and in closed spaces, so satellite imagery has little use. On the other hand, environmental crimes affecting large areas, or with a significant impact on the landscape are particularly fit for satellite applications, as in the case of forestry crime or illegal mining.

As a consequence, this report distinguishes according to the main sectors of application, which present the most consolidated usage; and other sectors, where uses are promising and growing, but have yet to reach full maturity. A full analysis of each area is available respectively in **Main sectors** and in **Other sectors**.

Main areas considered in this report are **Forestry crime**, **Illegal pollution**, **Fishery crime** and **Illegal mining**.

- Forestry crime is one of the sectors where EO is the most applied and successful, and one of the most serious among environmental crimes – estimates from UNEP state that from 10 to 30 per cent of all global timber trade is illegal, and up to 90 per cent in some tropical countries (UNEP 2014a). Satellite applications are multifaceted, and range from using optical imagery and time series to evaluate deforestation in remote areas, to advanced uses able to detect early signs of logging (and act pre-emptively).
- Illegal pollution is instead a rather varied set of offenses, including air, soil and water pollution. All three have a major impact on the environment and the health of communities: air pollution has been identified as the largest environmental health threat[39], soil pollution could affect up to 95 per cent of global food production (Ellerbeck 2023) and water pollution has been linked to almost half a million deaths a year (Koncagul and Connor 2023). Satellite applications are however very effective in relation to specific instances, particularly of water contamination (oil spills) and excessive emissions of methane and CO2 (which in most cases are however still not prosecuted).
- Fishery crime is a growing sector of application for EO, and a major offense:

39. Clean Air Fund website: Facts and stats on air pollution.

as one in five fish is considered caught illegally[40], the offense generates returns of up to 14.45 billion euros (Sumaila et al. 2020). Satellite applications are proving particularly effective, as they are quite accurate in identifying dark vessels possibly involved in fishery crime; as they use mostly SAR data, such tools can be used even with a significant cloud cover and at night. The implementation of AI tools is also significantly reducing the need for specialised analysis and the time employed during investigations.

- Illegal mining is also another area where EO contribution is relevant. The offense is also varied and ranges from unlicensed small-scale mining, to large operations performing activities beyond their concessions or with an excessive environmental impact. It is particularly relevant for some countries – gold from Colombia is estimated to be from 70 to 85 per cent illegally sourced (Nicholls 2023). EO has been used across all of them, from spotting deforestation activities linked to illegal gold mining in the Amazon, to the evaluation of the tailings and the impact on the landscape of nickel mines in Southeast Asia, with significant contributions also to major corruption investigations.

Other sectors considered are **Sand mining**, **Waste crime**, **Illegal construction** and **Wildlife crime**.

These four sectors present different levels of EO adoption. Sand mining is an issue receiving growing attention globally and satellite imagery is already applied to estimate damages done by illegal extraction in riverbeds. However, the scarce attention the crime received in the past, and complex, different criminal methodologies across countries have slowed down the adoption of satellite applications. This is similarly the case for Illegal construction, which could benefit significantly from EO, which has however seen only limited application until now. Waste crime is by contrast a cross-cutting, major issue that affects almost all countries, but only recently satellite have applications been successfully applied (mostly because of complex technical requirements). Wildlife crime, finally, is a sector where satellite data have a limited applicability, mostly because of the very high resolution and high revisit time required for effective uses, but applications are rapidly expanding and proving successful.

3.4 MAIN BENEFITS

Using EO in action against environmental crimes presents a significant number of benefits compared to using solely traditional techniques, in the majority of sectors and regions. Specifically, EO applications present two main advantages:

40. FAO website: Illegal, Unreported and Unregulated (IUU) fishing.

- **Saving time and resources on activities that are already done through alternative methods.**
- **Performing tasks that would be otherwise impossible.**

These two main benefits can be however expanded into a series of more detailed advantages, which can be summarised as follows:

- **Possibility to perform inspections on a distance**
- **Saving resources**
- **Automation**
- **Prevention and deterrence effect**
- **Completeness of information: Time and geographical coverage**
- **Objectivity**
- **Support to damage estimation and to restoration activities**
- **Cross-border investigations**

3.5 MAIN BENEFITS: TASKS THAT ARE OTHERWISE IMPOSSIBLE

Another core benefit is that EO performs tasks that would be otherwise impossible using traditional methodologies. Satellite data, especially but not solely multi-spectral ones, can provide information that are normally not available or very complicated to obtain. The Copernicus programme for instance offers historic data dating back to 2016, that are frequently used for forensic investigations to research events that took place in the past. SAR data allow for the detection of dark vessels that may be involved in fishery crime (see **Case 6**) or illegal waste trafficking, that would be very complicated to discover through traditional monitoring methods. This benefit is however multifaceted, and likely to expand thanks to the increase in missions and instruments available (see **Copernicus Sentinel Expansion missions**): EO can see environmental damage from a quantitative and qualitative perspective that would be otherwise impossible to detect (see **Support to damage estimation**), while also offering insights on early signs of environmental crime, so as to take pre-emptive action (see **Prevention and deterrence effect**).

3.6 DETAILING ADVANTAGES IN USING EO

3.6.1 Possibility to perform inspections on a distance

Advantages in terms of safety and health

The possibility to perform inspections at a distance is particularly relevant for sectors such as illegal waste disposal or pollution, since it allows officers to understand in advance the situation they will confront, and to prepare accordingly where health or safety risks exist. Furthermore, it permits officers to conduct investigations in regions where there is a significant security risk, such as in areas controlled by organised crime groups (OCGs) or local militias (as in the case for instance of Myanmar, see Case 2). Traditional inspections can also be complicated because of privacy and other regulations, and because inspecting private property would require a warrant in most cases. The use of satellite data in the vast majority of cases does not require prior authorisation, and does not face any limitation in terms of privacy (Kannegieter 2023, Interview 28).

3.6.2 Saving resources

Traditional monitoring also would require generally a substantially greater amount of resources, usually in terms of compensation for staff, fuel, equipment and other expenses. The bulk of data used in EO against environmental crimes are by contrast either free, or relatively cheap (especially if purchases are coordinated among national institutions) (Interview 32). This is also true for some analytical tools, such as those for the detection of deforestation or dark vessels (see **Main areas of application: Fishery Crime**), which can be freely employed by any interested user.

EO also reduces the time and resources needed to prepare investigations. This could be done by a preliminary examination of the territory, to flag the most suspicious locations and give priority to inspecting these (see **Case 1**). Enforcement agencies or prosecutors could also investigate an area where they received a report or a complaint regarding an environmental offense, to understand whether the information is accurate before deploying resources on the ground. Such a system has been systematically applied in Costa Rica by the administrative environmental court since 2022, and has significantly increased the accuracy of investigations, and reduced the waste of resources due to unclear or insufficient information (Interview 16).

3.6.3 Automation

Increasing accuracy and decreasing costs

Automation is also one of the key advantages in using EO against environmental crimes and is correlated to the recent development of AI. Several analytical tasks that are performed on satellite images can indeed be done either manually by expert users, or automatically through the design of dedicated AI applications. The number and variety of such tasks is significant, as potentially almost everything can be automated: the detection of suspicious objects (such as illegal waste disposal sites, or deforested areas), the detection of dark vessels or oil spills, even the estimation of wildfire damages. Automation presents a number of ad-

41. Satelligence website: RADD: Public radar-based deforestation monitoring.

vantages: it remarkably accelerates the analysis of satellite data, even increasing its accuracy in some cases (Interview 35); it makes the functioning of the application independent from the available resources; and it makes the monitoring more systematic and structured (as it would happen at fixed points in time). Automation also decreases the need for specialisation by players in the environmental crimes sector, as it resolves the requirement for full-time involvement of expert users to run the system. Although updates and maintenance are key to the long-term functioning of EO applications, automation significantly decreases the need for intervention by developers and experts, and thus the costs of running such systems (which could be minimal, once they are fully developed).

3.6.4 Prevention and deterrence effect

Prevention of crimes and a deterrence effect are also additional benefits from using EO, although not among the most common. Some applications indeed offer the possibility to discover the early signs of offenses, and to act before the crime is committed. In deforestation cases, for instance, the full clearing of a forest is usually preceded by the opening of roads under the canopy, by selective cutting of valuable species and by other preparatory actions. These are discoverable using tools such as the RADD system (included in the Global Nature Watch platform), which gives almost real-time alerts for canopy disturbances[41]. Applications aimed at counteracting wildlife crime are also almost entirely focused on the prevention of poaching (see **Case 8**); the analysis of satellite data, and the combination with other kinds of information, allows rangers in national parks to distinguish areas where the risk of wildlife crime is higher, and thus to prepare accordingly.

The constant monitoring offered by EO on small and large territories has also had a deterrence effect in some instances; this has been for instance the case in Flanders (see **Case 4**). With regard to this application, farmers monitored by the system deployed by Belgian authorities committed significantly less offenses, particularly in terms of illegal landscape changes (the main focus of the application). This has been identified as a direct consequence of the publicity the system received through awareness campaigns and the support of national media (Interview 37). Deterrence effects are not limited to this case, and are usually associated with continuous, structured satellite monitoring of the territory, as in the case of forestry and fishery crime in Costa Rica (Interview 16).

3.6.5 Completeness of information: Time and geographical coverage

Full time series and complete geographical coverage

Satellite data offer an array of information that is in many cases not available through other sources, particularly in terms of completeness. Databases such as those provided by the Copernicus programme have complete time series in most cases since late 2016, with a global coverage. Investigators can therefore perform analysis of the territory close to the date when the offense took place, even if enforcement agencies were not monitoring the area at the time. This also allows for the discovery of potential precursors: in some cases, wildfires or a clear cut are preceded by weeks of selective cutting, as loggers take the most economically valuable species before razing the entire area to the ground. The ample coverage of such databases also allows investigators to detect the construction of nearby infrastructure (air strips in the middle of the forest near mines, or roads under the canopy). This can in turn give information about key elements in investigations, such as criminal methodologies, trade routes and involvement of other players (such as freight operators, freight forwarders or smelters). Completeness of information also means that investigations can focus on entire regions: traditional methodologies often involve a "spot" collection of data – meaning that observations are limited to a specific place and a specific moment. EO instead offers a seamless image of vast areas, which in turn allows for a complete analysis of the full extent of the offenses.

3.6.6 Objectivity

An "undeniable" picture of the crime

Satellite data require extensive processing, and follow a series of high standards and procedures. As a consequence, they are not easily altered, and are significantly more reliable that other, traditional sources of evidence even without certification or validation processes. They offer thus solid proof that could be particularly effective when other evidence collected on the ground could be doctored. Satellite data offer a clear, reliable, hard-to-deny kind of evidence; this has proved crucial in a number of cases, particularly in addressing corruption. Indeed, corrupt officials could prevent access to locations affected by crimes, or delay inspections until they are no longer relevant to the case, or to hide evidence. Using EO, enforcement agencies can inspect sites at a distance without prior notification and without the need to involve potentially corrupt officers, obtaining clear, hard-to-question evidence of the present and even the past. Even if some governments have denied satellite evidence in the past (as in the case of estimates for palm-oil wildfires in Indonesia), this has usually referred to nation-wide estimates of phenomena such as deforestation. This research has encountered no instances in which satellite evidence has been refused as proof in individual cases (for either political or technical motivations).

3.6.7 Support to damage estimation and to restoration activities

Fully understanding the environmental damage

EO can offer information on a variety of issues, including the extent of damage inflicted by the environmental offense, and estimation of the restoration activities required. It can understand for instance the damage due to collapse of a dam holding mine tailings, across the whole surrounding territory; or evaluate the amount of CO_2 or PM2.5 emitted during a wildfire, and the damage to property and health (see **Case 3**). This is a crucial element: in environmental cases, it is fundamental to understand the extent of offenses which are often well-hidden or very hard to detect, and thus to determine appropriate sanctions. In all cases analysed by this research, EO has proved much more effective and cheaper than traditional methodologies for damage and restoration estimates.

3.6.8 Cross-border investigations

Addressing transnationality of crimes

EO offer a seamless vision over entire regions, which is not limited by political borders. In this sense, it is able to capture a full picture of offenses that are very frequently transnational by nature: this is the case for instance concerning fishery crime, forestry crime and waste crime, which are sectors where criminals exploit national borders and insufficient collaboration among different police forces to hide their crimes. The data offered by EO can instead uncover routes crossing multiple countries (as in the case of trade of illegal minerals in Southeast Asia), illegal operations affecting both sides of a border (as in the case of illegal logging in the Amazon) or OGCs operating in one country while residing in another (as in several instances of fishery crime).

3.7 MAIN OBSTACLES

Despite the benefits highlighted above, the uptake of EO remains widely below its potential. This is due to a set of obstacles that differ across sectors and use, but are generally consistent throughout all areas, and in many cases not only hinder the mainstreaming of EO usage, but even its evolution beyond the project stage. While this report discusses the hurdles specific to main areas of environmental crimes in the **Sectoral analysis**, this part considers obstacles that are common across all areas. The section also provides a few indications on tools and actions available to address key limitations. These are divided into:

- **Technical obstacles**, focusing on technological limitations, issues caused by local geography or troubles in data integration.
- **Political obstacles**, dedicated to the perception of – and often hostility by – authorities and politicians regarding satellite applications.
- **Operative obstacles**, related to issues in the adoption of these tools by enforcement agencies and NGOS in their investigations.
- **Judicial obstacles**, focusing particularly on the troubles faced by prosecutors and judges in their use of EO data.
- **Legislative obstacles**, which concentrates on inadequate legislative frame-

works or scarce integration of satellite tools into laws and regulations.

- **Socio-economic obstacles**, related to the economic situation of the local population, which enables the perpetuation of environmental crimes.

3.7.1 Technical obstacles

In several cases, technical limitations still represent one of the major hurdles in the use of satellites against environmental crimes, and one of the most complicated to solve, as new missions may be required to address the problem. Nevertheless, the evolution of software, the integration of satellite data with other information, and other new instruments may be able to accelerate this process (see **Recommended actions to improve EO**).

Spatial resolution of images has been reported as the main issue in most cases (Interviews 1 to 37); indeed, while the Sentinel satellites have recently improved this specification (from the average 30 meter resolution of Landsat, to the 10–20 metres of Sentinel-2A/2C and 2B, for instance)[42], in many cases this is still too low to investigate environmental crimes that would require a much higher resolution (50cm to 1m). What has been described is for instance several illegal waste disposal cases in Eastern Europe, where dumping sites could be spread throughout the territory but be too small to be identified through low-resolution imagery (Interview 12). This is equally a major issue in investigating instances of poaching or wildlife trafficking (see **International treaties**), since even a land animal as large an elephant has proven very hard to identify through satellite analysis (Interview 13).. While higher resolution images can address this issue, their high cost and the relatively high frequency or number of photos that are required by most environmental investigations often discourage their employment. Spatial resolution limitations are likely the main reason why some sectors show a greater and more rooted employment of satellite data (illegal mining, illegal logging), while others are still lagging behind (fishery crime, wildlife trafficking). Authorities have tried to circumvent such obstacles through different methodologies, such as tip and cue (i.e., scanning large territories thorough low resolution images, and then focusing on specific areas with high resolution), or mixing free high-resolution, low-frequency images such as those offered by Google Earth, with lower resolution, high-frequency ones, like those offered by Copernicus or Landsat (Interview 16).

Impact of different geographies

Geography is also another major obstacle, although the increasing employment of multispectral images (especially through dedicated platforms, such as Skylight) has offered significant improvements in recent years. The persistent cloud cover of some regions has been a major hurdle in the use of systems against deforestation or illegal mining, such as DETER; this is particularly relevant since tropical

42. Copernicus website: S2 Mission.

regions such as the Amazon or Southeast Asia are at the same time more exposed to deforestation, and more frequently have a solid cloud cover (particularly during the wet season, but also relevant at other times of the year). Also the haze caused by wildfires has proven a relevant obstacle in investigations related to, for instance, the illegal expansion of palm oil plantations. Multispectral images and SAR ones in particular have proved effective, as the latter are not blocked by clouds and have multiple uses (especially for land use change, deforestation, oil spills and fishery crime). However, the availability of SAR images is scarcer compared to optical images. This is because SAR relies on an active sensor, one that transmits its own microwave pulses rather than detecting ambient light, which constrains acquisition frequency and geographic coverage, ultimately limiting its usability.

Finally, the detection of potential environmental offenses through the use of AI and other automated systems could result in a number of false positives (Interviews 13, 36 and 37), or simply an excessive number of detections, which could in turn discourage action by enforcement agencies (because of decreasing confidence in the instrument, or because of the inability to choose the most salient cases among all those detected).

3.7.2 Operative obstacles

Insufficient resources of enforcement agencies

The employment of EO data by enforcement agencies is often limited by limited awareness and by high turnover among departments, which makes the development of consolidated expertise within units particularly complicated.

Lack of resources on the part of enforcement agencies is however the most common challenge. Frequently, agencies do not have the staff required to perform inspections in the sites highlighted by EO applications, which leads to a significantly smaller number of confirmed detections and investigations than the potential. This is mostly due to budgetary reasons, which affect both the general resources available, and those specifically dedicated to EO. Indeed, the budget underpinning law enforcement in the context of environmental crimes is per se often insufficient to allow a good level of investigation and prosecution, and the use of EO usually increases costs. In some cases, certain countries have significantly increased the funds allocated to combating environmental crimes through the use of technologies in light of striking events, such as the devastating forest fires that occurred in Indonesia in 2016 (Tacconi et al. 2019). Other countries have however faced an acceleration and deceleration phase, such as Brazil which spent USD 1 billion/year on forest conservation policies from 2000 to 2014. In the following years, the budget decreased by 40 per cent from 2013 to 2016, which severely limited the country's investigation and prosecution capacity.

In addition, perpetrators may try to invalidate satellite data. For instance, the digital tracking systems that trucks transporting wood must display according to Romanian law were boycotted by truck drivers, who would use fake GPS loading points (Associated Press 2024). Another emblematic example concerns the multiple strategies that loggers in the Brazilian Amazon rely upon to evade enforcement of the laws restricting deforestation. Among others, loggers use lumber extraction methods that are less likely to be detected by satellite surveillance. The prosecution of a criminal organisation that deforested 290 square kilometres of the Brazilian Amazon from 2012 to 2015 was only possible because Indigenous communities in that protected area reported the illegal activity. Satellites had not detected the clearing of the forest as the loggers kept some tall trees to preserve canopy cover and operate undetected by satellites (Acebes et al. 2019).

3.7.3 Judicial obstacles

Privacy and other regulations

The use of EO satellite data faces judicial obstacles as well. Indeed, satellites may be used in trials if admissible. However, inaccurate data stemming from miscalibrated sensors or algorithmic errors undermines the reliability and accuracy of satellite imagery and data. In addition, satellite data used in court must be proven authentic, namely free of manipulation, and in compliance with privacy and personal data protection requirements. This is because the observation of private spaces or the location of a person via satellites may reveal information about individuals' private lives. In the US, for instance, a court found remote sensing more invasive than the human eye and concluded that information that could be derived from satellite data violated the appellant's privacy (U.S. Supreme Court 1986). This is however a relatively limited instance, that only concerned VHR images and the US. In addition, the collection of personal data by satellites via images, videos, sound and geo-localisation data may also be in contrast with data protection legislation (Coffer 2020). The issue of privacy may also arise beyond individual data privacy; for example, satellite data can reveal sensitive information about collective groups, such as vulnerable populations and refugee camps (Undseth and Jolly 2026). Hence, privacy rights need to be assessed and reconciled with other rights and interests, such as the prosecution of an environmental crime.

Combination of different evidence

Another key challenge concerns the need to often combine satellite data with other sources of proof in order to establish the liability of the perpetrator. Indeed, whereas satellites can establish if and what environmental criminal offence has occurred (correlation), they cannot link the fact to a specific person or company (causation). This has been a key obstacle in the context of the Amazônia Protege programme, launched in 2017 by the Brazilian Federal Public Prosecution Service to hold illegal deforesters liable for environmental damage through lawsuits. As part of this programme, 3,561 public civil proceedings have been filed thanks to the combination of satellite images, which indicated the occurrence of deforestation, and public databases naming those responsible for the deforested area (Almeida et al. 2022). Out of the 650 cases of illegal deforestation with a first instance verdict as of October 2020, only 8 per cent convicted the perpetrators (51 cases). The lack of proof linking the deforestation event to the perpetrators was one of the obstacles to conviction. In addition, most judges rejected the reports based on satellite images without field inspections, and the lawsuits lacked identification of defendants. However, rulings from the second instance court have overturned some of these decisions.

3.7.4 Legislative obstacles

Lack of adequate legislation, and slow speed of adaptation

The limited concrete application of satellites to prosecute environmental crimes may also relate to the absence of specific legal provisions regulating their use in this particular field. For instance, both Belgium and the Netherlands do not have any specific norm either impeding or legitimising the use of satellites as a proof of criminal offence. Although this flexibility may potentially encourage the use of satellites to bring a case before a court, such indeterminacy actually discourages the use of EO data. In addition, the lack of a legal reference implies the absence of legal clarity regarding how, by whom and under what circumstances satellites can be used (Isarin et al. 2024). Finally, it is relevant to note that there is currently insufficient input to start using satellites in environmental crime investigations even at the supranational level. Emblematically, the new EU Environmental Crime Directive does not contain any reference to satellites. This is arguably a missed opportunity to support member states in adopting new technologies in this field as well as to enhance harmonisation and coordination at the national level.

In addition, legal advancements take much more time than technological advancements. Hence, the improvement of satellites as well as algorithms and data analysis is so rapid that related legislation becomes inevitably outdated. This undermines not only the efficacy of the law but also of the methods prosecutors use to enforce it (Interview 31).

3.7.5 Political obstacles

Political obstacles mostly relate to the perception of satellite data by national governments, regional administrations and other entities, and their possible opposition to its use because of the influence of national interests, corruption or the mistrust generated by the perceived “foreign” origin of sourced data.

In recent years, several governments have denied or even actively opposed the results brought by the analysis of satellite evidence on environmental issues. Most notably, in 2019 the then-president of Brazil, Bolsonaro, publicly claimed that the data gathered by the INPE on deforestation in the Amazon were false (BBC 2019), and shortly thereafter sacked the director (Escobar 2019) and proceeded to heavily defund the institution (Margolis 2022). This was done in order to promote the agriculture-driven deforestation that Bolsonaro strongly sponsored, and which would have been, in several cases, against the strict laws Brazil already had in place at the time. While this is one of the most relevant cases, it is not the only one: in 2020, French researcher David Gaveau had to leave Indonesia after a rift with the national government, which opposed the estimation of wildfire damage in the country based on satellite analysis (Rochmyaningsih 2020). Indonesian authorities did not directly oppose the use of satellites (as in Bolsonaro's case), but did not agree with the interpretation offered by the researcher (although without offering supporting evidence). Such disputes have also arisen in other cases, for instance when the country was accused by neighbours of causing the haze that covered part of Borneo or the Malaysian straits in the 2017–2020 period (Chan, 2019).

Role of corruption

In these cases, the opposition was largely triggered by entrenched national interests (the production of palm oil in Indonesia and the expansion of agricultural land in Brazil), but often corruption also plays a crucial role. Authorities that granted illegal mining licenses, or turned a blind eye on illegal operations, would also discourage the use of EO for monitoring the landbase, for instance through high-level corruption (UNICRI 2025). Corrupt officials could prevent the digitalisation or dissemination of concession maps (Interview 34), so it would be impossible for civil society, and hard even for enforcement agencies, to check for violations by comparing these maps to satellite images (Interview 30).

In many cases, opposition towards satellite applications does not happen as a direct and explicit prohibition by corrupt authorities or politicians, but through slowing the adoption of satellite applications, blocking or watering down initiatives, and by reducing the overall awareness on the convenience and availability of EO data.

Impact on the work of NGOs and international organisations

In some cases, international organisations (Interview 6) and civil society (Interview 4) have faced troubles in promoting satellite applications because of the perception on the part of national authorities of data produced by foreign space agencies as unreliable and potentially subject to political interference. While this has never translated into direct opposition, entities operating in several countries in South America (Interview 4) and in Sub-Saharan Africa (Interview 7) have sometimes faced strong scepticism by a number of institutions: enforcement agencies, national governments and even judges who distrusted adopting satellite-based applications or platforms, as they believed the data may have been manipulated by the foreign countries producing them (despite the lack of any evidence showing that this would have been a possibility). This opposition has in turn slowed the adoption of such tools, as well as increased the burden of proof related to satellite evidence.

3.7.6 Socio-economic obstacles

Poverty

Socio-economic obstacles encompass the economic factors that constrain the broader application of satellite observation in monitoring and combating environmental crimes.

Poverty, compounded by aggravating circumstances such as armed conflict and climate change, pushes a growing share of the population towards environmental crime and fosters resistance to monitoring systems. Where individuals' subsistence depends on activities deemed criminal, as is frequently the case with illegal fishing in developing countries, communities may actively seek to circumvent or undermine satellite-based detection mechanisms. In practice, this, for example, entails not using glocalisation systems to detect deforestation, or providing false information in public surveys, such as stating that EO applications do not work because of a lack of signal in their area.

Impact of OCGs

This dynamic is further exacerbated by OCGs, which derive substantial benefits from environmental crimes and often coerce the most economically marginalised segments of the population into participation through violence. This coercion manifests through intimidation of local informants or corruption of community leaders. This is often the case when the state does not have control over parts of its territory and therefore cannot protect these areas from criminal actors.

Together, these two dynamics are self-reinforcing. Poverty drives participation in environmental crime, which consolidates the power of OCGs, whose corruption and violence further erode the state capacity needed to translate satellite data into enforcement action.

SECTORAL ANALISYS

1. FORESTRY CRIME

Forests and peatland on the Likouala-aux-Herbes in Congo DRC. Contains modified Copernicus Sentinel data (2025), processed by ESA.

FORESTRY CRIME

Numbers

ESTIMATED VALUE
51-151B$
15-30% OF TOTAL TIMBER

GEOGRAPHIC SCOPE
50-90%
OF LOGGING IN TROPICAL COUNTRIES

DEFORESTATION KEY TREND
TO 10.9M HA/YR (2015-2025)
VS 17.6M HA/YR (1990-2000)

Benefits

MONITORING SCALE
DETECTS DEFORESTATION IN INACCESIBLE PLACES.

INCREASE ACCESS
PREDICTS FUTURE DEFORESTATION PATTERNS.

CRIME CONVERGENCE
IDENTIFIES EARLY SIGNS OF CLEARING TO UNCOVER ILLEGAL MINING, DRUG TRADE, ETC.

Obstacles

TECHNICAL
FOREST DEGRADATION AND SELECTIVE CUTTING ARE HARD TO DETECT WITH LOW-RESOLUTION IMAGES. CLOUD COVER LIMITS OPTICAL SATELLITES IN TROPICAL REGIONS. SAR IS IMPROVING BUT NOT YET UNIVERSAL.

LEGAL
SATELLITES ARE ABSENT FROM KEY TREATIES (E.G. CITES). COURTS IN SOME JURISDICTIONS REJECT SATELLITE DATA WITHOUT FIELD CONFIRMATION.

OPERATIVE
DETECTION IS NOT ALWAYS MATCHED BY CAPACITY TO ACT ON THE GROUND. INCOMPLETE OR UNDIGITISED FOREST INVENTORIES PREVENT IDENTIFYING VIOLATIONS IN PROTECTED AREAS.

SOCIO-ECONOMIC
BUDGET CUTS REDUCE SATELLITE SPECIALISTS AND FIELD INSPECTORS. POVERTY PUSHES COMMUNITIES INTO ILLEGAL LOGGING.

POLITICAL
CORRUPTION ENABLES FALSIFIED PERMITS AND SILENCED ENFORCEMENT OFFICERS. POLITICAL ELITES OPPOSE SATELLITE EVIDENCE. ARMED GROUPS SABOTAGE FINDINGS AND THREATEN RANGERS.

1.1 OVERVIEW OF APPLICATIONS IN THE SECTOR AND RECENT EVOLUTION

Forestry crime is one of the most common among environmental crimes, and likely the one where satellite applications are the most consolidated and, to some extent, the most effective.

Definition of forestry crime

Forestry crime covers offenses along all the different steps of the forestry supply chain, from the unauthorised clearings of forests to the laundering and trade of illegally cut timber, including protected species under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)[43]. Satellite applications are largely employed to detect illegal logging where the activity is taking place, although Earth Observation is also used to analyse other parts of the supply chains (logging camps, areas used to store timber, ports and trading routes), as well as other violations.

The success behind the use of satellites against illegal logging and forestry crime is the result of a combination of factors. Satellite images are particularly fit to detect clearings as they are easily visible from space, making the detection of violations possible also in inaccessible areas, or where the security risk is high. While forest degradation and selective cutting require a higher resolution to be identified, larger clearings can also be discovered with low-resolution images; this is one of the reasons why forestry crime has been the first environmental crime sector to witness the application of EO, already since the late 90s and early 2000s, which in turn has consolidated its use. The current, increased availability of multispectral images and the expansion of software for the analysis of data have recently increased the range of uses, including also applications able to predict future deforestation patterns. AI and deep learning have also played a crucial role in expanding the use of EO in forestry crime, since they allow for a much faster and almost completely automatic detection of logged areas and estimation of biomass (which is used to monitor degradation) (Jelas et al. 2024).

Kinds of data employed

Optical images are the most commonly used across all applications. They are employed by a variety of players (see below) to estimate logged areas and their impact on forests, as well as the opening of infrastructures (roads in particular, but also ports and other trading routes) that are connected to illegal deforestation. Multispectral images are also increasingly

43. Interpol website: **Forestry crime**.

being employed for a variety of reasons; above all, missions such as ESA's Sentinel-1 are able to penetrate the cloud cover that is often persistent over tropical forests (the Amazon and Borneo in particular), and which has been a historical obstacle to the application of EO against forestry crime (Molnar and Kiraly 2025). High-resolution satellites have also traditionally been required to detect canopy disturbances and other less visible forestry crime, such as the selective cutting of valuable species in primary forests – issues which, although less impactful than massive clearcuts, have however a significant impact on the biodiversity and the health of forests (MAAP 2020). The analysis of multispectral data is however offering a relatively cheaper and more available alternative to high-resolution images in the detection of these less visible destructive actions, particularly in conjunction with techniques such as polarimetry and interferometry (Reinisch et al. 2020). These tools are also used to try and predict deforestation patterns; illegal logging is indeed usually preceded by a series of actions, such as the opening of roads or logging camps, while clearcuts are often anticipated by the selective cutting of high-value species. Identifying such actions offers a chance for enforcement agencies to act before full-scale logging takes place. Several platforms now offer automatic detection systems that link AI analysis to Sentinel-1 imagery, providing alerts every six to 12 days; this is the case for the Foliage Penetration Reconnaissance, Surveillance, Tracking and Engagement Radar (FORESTER) Service, for instance (ESA 2024), and for the Radar Alerts for Detecting Deforestation (RADD) Forest Disturbance Alert (Wageningen University and Research 2025). The latter has been notably included in the Global Nature Watch application; it can thus be freely used through the platform, which is free and open to the public[44].

Platforms

Indeed, several platforms have been developed to address forestry crime through EO. Global Nature Watch, the tool developed by Global Forest Watch (GFW), is likely the most complete and is used throughout the sector; the platform has existed since 2014, when it was launched by the World Resources Institute (WRI). It has since been used to combine a variety of data (at first mostly from the National Aeronautics and Space Administration's (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) sensor) to offer both a large-scale analysis of deforestation across the globe, and insights into logging activities at the regional and local level. Through the integration of information about, for instance, mining concessions and protected areas, the platform offers a wide perspective on forest use and change, and it is indeed used by a variety of different

44. Global Forest Watch: **Deforestation alerts (RADD)**.

players, from local and international NGOs to enforcement agencies. Other platforms are also employed against forestry crime; while Google Earth Engine is likely the most common after Global Nature Watch (Interviews 16, 17 and 18), some national agencies have also developed their own tools. This is the case for instance for Inspectorul Pădurii (Forest Inspector), realised by the Romanian environmental police to address the persistent issue of illegal logging in the country[45]. The platform is part of the "Sumal 2.0" system and also integrates data about timber trade and transport to help connect illegal shipments to illegal logging sites (and thus identify illegal loggers and buyers).

EUDR

Finally, it is worth noting that EO is being increasingly used to comply with the rules imposed by the EU Deforestation-Free Regulation (EUDR), which forbids the entry into the European market of seven key agricultural commodities if they have caused deforestation in the producing country. As a consequence, the EUDR requires traceability systems that are based on geolocalisation through Global Positioning System (GPS) coordinates[46]; competent authorities can use platforms such as Copernicus Browser or Google Earth Engine to check if the area has been logged to produce the traded commodities.

1.2 MAIN PLAYERS INVOLVED

National authorities

Satellites are significantly used by a wide range of national authorities in their operations against forestry crime. National organisations or bodies with a mandate on forest protection or space research, among others, have developed or promoted multiple satellite-based solutions in order to support police, patrolling and enforcement officers in the detection of illegal deforestation activities. These include the development of apps based on satellite and observation data to send deforestation alarms in precise locations, such as the one developed by the Kenya Forest Service, and the use of satellite images to promote effective monitoring and patrolling by forest operators to detect forestry crime activity, such as in the case of Finland for deforestation activities near bodies of water (YLE News 2023). Similarly, competent ministries have also turned to Geographic Information System (GIS) service providers to create software based on satellite images to identify changes in the forest cover indicative of forestry crime, in turn enabling authorities to become aware of any forestry crime in almost real time. This is true of the above-mentioned Forest Inspector,

45. Romanian Ministry of the Environment: **Forest Inspector** and see WWF-România, 2023.
46. European Commission Website: **EUDR Implementation**.

developed by TerraSigna upon request of the Romanian Ministry of Environment, Water and Forests and comprising a geographic information system that integrates radar and high-resolution satellite images from Sentinel-1 and 2, Landsat, OpenStreet and Google Maps. The platform enables police officers and the broader society to identify the loggers, the type of wood being cut and the whereabouts of the illegal activity (Colantoni et al. 2022b).

In addition, national police forces are also developing satellite applications that will allow them to track the routes of illegal timber trade, while identifying the species, country and the region of origin through the correspondence of genetic tests and wood anatomy samples. This is what the Servicio de Protección de la Naturaleza (SEPRONA) is doing by creating scanners to enable customs officers to trace the origin of wood and eventually declare its legal or illegal origin, using only mobile phones (Colantoni et al. 2022b).

Focus on Brazil

Key achievements have been also reached by the Brazilian INPE, which has implemented several satellite applications, most importantly PRODES and the Sistema de Detecção de Desmatamento em Tempo Real (DETER), to send warnings about potential illegal deforestation activities in the Amazon. These data are accessed directly by environmental agencies, such as the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) and the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), as well as the Public Prosecutor's Office, so that they can act promptly against logging. PRODES, a system created by INPE in 1998, collects satellite data coming from Landsat every 16 days with a resolution of 30 meters. In light of its limitations, in 2004, INPE launched DETER, which was a true game-changer for an area historically affected by rampant deforestation (McNeely 2024). DETER is a near real-time alert survey of deforestation based on satellite imagery and used by IBAMA for enforcement purposes. Until 2015, DETER detected areas of deforestation larger than 250 square meters and updated its public-access satellite images every three months. The system was improved through DETER-B, and now a team of experts at INPE is responsible for daily visual interpretation of the satellite images. In addition, several senior auditors perform daily validation of the data received by DETER-B.

NGOs

NGOs also play a key role in developing satellite-based initiatives documenting deforestation and forest degradation relevant for prosecution in court and for raising awareness in society. NGOs' use of satellites contributes to fighting forestry crime in multiple ways, including by providing annual global maps of forest loss or by implementing online platforms to identify deforestation operations by detecting logging roads, monitoring activities in protected areas or national parks, and by comparing the permit areas with the true scale of the operation. In addition, NGOs use satellite images to raise awareness on forestry crime and to empower society. Relevant examples include Global Forest Watch, a digital tool developed by the World Resources Institute, making the latest satellite data from Sentinel-2 and Landsat 8 available to users to protect forests from crimes (Interview 11). Satellite data are conveyed in a comprehensible, non-technical way to actively involve local communities and households in the detection of illegal deforestation. Finally, NGOs play a relevant role in protecting the rights of Indigenous groups affected by deforestation and forest degradation by empowering them on the use of technology to defend their territories. In Brazil, for example, WWF supports a number of Indigenous associations to use satellites to monitor 22 territories covering an area of 6.4 million hectares.

Role of Interpol

Interpol is a prominent actor that provides support to law enforcement against forestry crime. It assists international operations against illegal deforestation and the illegal transportation of timber, while coordinating the exchange of information in real time between national authorities and Interpol's National Central Bureaus in transit and destination countries. Two Interpol-led initiatives emblematically show the relevance of satellites in their operations. In 2012, Interpol launched a global initiative called Law Enforcement Assistance for Forests (LEAF), now known as Global Forestry Enforcement (GFE), with the aim of supporting law enforcement working across the entire timber supply chain to tackle forestry crime. To do so, satellites have proven essential to track the vessels transporting illegally logged rosewood from Madagascar to East Africa, and allowed Interpol to alert the countries concerned before the vessels arrived in port. Similarly, in 2014, Interpol conducted Operation Amazonas I, an initiative targeting forestry crime and the trade of illicit timber in Brazil, China, the Dominican Republic, Mexico and Peru. By relying on satellites, the operation uncovered a range of illegal activities, including trade in illegally harvested timber products, the sale and use of fraudulent permits to launder timber, and the mislabelling of timber exports.

Relevant responses against forestry crime have been also provided at the regional level. For instance, in 2008, the Central African Forests Commis-

47. WWF website: **Amazon on the brink**.

Regional institutions

sion (COMIFAC) established a subregional agreement involving the environment and forestry ministries of eight countries to facilitate law enforcement coordination on timber-related production and trade. The agreement creates a sub-regional information system in the form of a computerised database known as the Central African Forest Information System (SIFAC), which collects and stores information on forests from satellite images as well as from cartographic data and in-field missions[48].

EU level

At the EU level, the Green Deal has put great emphasis on the use of satellites in protecting forests and fighting against forestry crime. The EUDR requires agricultural products to be deforestation-free, therefore banning those commodities that were produced illegally, on land deforested after 31 December 2020, or that are not traceable from the EU market. To verify whether the geolocation of declared products is linked to deforestation, satellites may be used. In particular, Copernicus, in addition to optical satellites and SAR data, can provide forestry stakeholders with global data with a high acquisition frequency. Likewise, the New EU Forest Strategy for 2030 aims to develop strategic forest monitoring, reporting and data collection by leveraging Galileo and Copernicus services. The Commission will develop EO-based monitoring tools for forests that may be operationalised by Copernicus and taken up by the Forest Information System for Europe (FISE) as part of the integrated forest monitoring system.

1.3 MAIN ADVANTAGES OF USING SATELLITES IN THE SECTOR

Some of the main challenges in preventing and tackling forestry crime relate to the difficulties in monitoring large areas of forest land due to the remoteness of these areas and the limited financial and human resources available to forestry enforcement agencies for such monitoring. In addition, traditional monitoring methods often rely on in-field inspections which can hinder quick action against forestry crime. Remarkably, prior to the introduction of satellite applications to detect deforestation in 2018, monitoring in Finland was based solely on forest declarations and field inspections by sampling (Yle News 2018) (ESA, 2019). The adoption of satellite imaging technology by the Finnish Forest Centre has resulted in a tenfold increase in the number of forestry crime detected (Teivainen 2021).

48. See **Central African Forest Information System (SIFAC)** website.

In this context, satellite imagery analysis is by far the most relevant and most extensively used tool to identify forestry crime activities and to focus enforcement actions where these may have occurred (Colantoni 2023). Optical satellites use visible light to capture images of the land cover. They provide high-resolution images, making it easy to identify changes in forest cover. Yet, their effectiveness can be limited by weather conditions, as clouds can limit visibility. By contrast, radar satellites can capture images regardless of weather conditions. They emit radio waves and measure the time it takes for them to bounce back, providing data on forest structure and density. The combination of these models allows for data accuracy and clarity (Rajao et al. 2013). In addition, akin to illegal mining, satellite images could be used to assess whether legal permissions align with the actual forest area. Furthermore, satellites have the major advantage of being able to trace the route of wood products from country to country. As forestry crime is often fuelled by international demand, wood traders' declarations of legitimate wood origin could be checked against satellite imagery (Beach 2015).

Crime convergence

Finally, satellite images can emphasise the so-called crime convergence. Indeed, environmental crimes often occur in silos, whereby illegal mining often causes illegal deforestation, facilitates drug trade and drives money laundering. For instance, satellite images demonstrate that one of the main causes of deforestation in the Madre de Dios region in Peru is illegal gold mining and unauthorised agricultural projects (Bargent 2019, Interview 11).

DETER

The satellite systems developed by the Brazilian INPE emblematically show the benefits of using this technology to fight forestry crime. In particular, although PRODES and DETER have different databases and teams, the data they provide complement each other well. Indeed, DETER can spot critical areas for deforestation, while PRODES can look at them more closely. PRODES uses different satellite images to get information from cloudy areas that Landsat alone is unable to identify, such as those coming from CBERS, the result of a partnership between Brazil and China, and Sentinel from ESA. PRODES generates annual deforestation rates, supporting long-term public policies to contain the destruction of the Amazon. By contrast, DETER provides for a near real-time alert survey of deforestation based on satellite imagery. Initially DETER detected areas of deforestation larger than 250 square meters, updating its public-access satellite images every three months. Yet, DETER faced several challenges in identifying forestry crime due to cloud cover and adverse weather conditions. The lower resolution of the sensors used by DETER was compensated for by daily observation capacity, making the system an ideal tool for quickly informing enforcement agencies of new changes in forest cover. Yet, police officers discovered that deforesters were clearing areas smaller than 250 square meters to avoid detection and had started to conduct illegal operations at night and during the rainy season (Gonzales 2019). As a consequence, in August 2015, INPE began operating a new version of DETER (DETER-B). DETER-B is now able to identify and map, in almost real time, deforestation as well as forest degradation with a minimum area of around 3 hectares.

1.4 MAIN OBSTACLES

Technical obstacles

Forest degradation and cloud cover

Despite significant improvements, satellite applications against forestry crime still face some technical limitations. While deforestation (i.e., the clearing of forest land and its conversion for other uses) is relatively easy to spot, forest degradation (i.e. the loss of ecological health of a forest due to human activities) remains complicated to monitor using low- and medium-resolution images as the changes may be too minimal to be detected. Modifications in the forest cover that contribute to forest degradation, such as the planting of productive species into primary forest, are also often hard to detect through optical images – details regarding forest structure in most cases require very high resolution to be fully appreciated.

Optical images also face the challenge of cloud coverage, and even the haze caused by fires can represent a significant obstacle. Despite a greater availability of multispectral images, forestry crime applications would benefit from a greater spatial and temporal coverage, particularly in regions strongly affected by cloud cover.

Political obstacles

Corruption

Forestry crime remains persistent largely because of pervasive corruption, political pressure and violence, which are key obstacles to satellite applications in this field, both within and beyond the EU.

Indeed, bribery of land officials can facilitate the issuance of falsified land titles or allow landholders to deforest more than is legally permitted. Corrupt enforcement officers can avoid reporting satellite findings, and automatic monitoring systems can be put offline by simulating a malfunction (Colantoni 2023). At the same time, corruption of police officers and public prosecutors could impair the use of satellites as a tool to monitor, investigate and initiate legal actions against forestry crime. In other cases, collusion between political and business actors has led to the falsification of forest inventories and harvest permits that are then validated by public officials – as well as to the exportation of rare wood species beyond what is prescribed by law (Browne et al. 2022). To pursue their own interests, policymakers and business people could therefore oppose the use of satellites to detect illegal deforestation. Satellite images in Bulgaria show, for instance, that the disappearance of primary forests in certain areas coincides with an explosive development of tourism (Dimitrova-Pichot 2014). Policymakers can also undermine the use of satellite by denying or opposing satellite evidence in relation to forestry crime (Rochmyaningsih 2020, BBC 2019). In addition, they can perpetuate the culture of impunity by hampering the use of satellites in investigations and in court or by passing legislation that harms the environment and seeks to indemnify illegal actors (WWF 2020).

Political pressure

Political pressure on judges may result in judicial inertia, where cases concerning forestry crime, wood smuggling and aggression against forest rangers are left in limbo for decades, resulting in the impunity of the perpetrators (Kindji 2021, European Parliament 2019). In addition, judges may discredit the use of satellites as legal evidence of forestry crime or deem the satellite data as invalid to let criminals involved in forestry crime avoid punishment and get back confiscated equipment through informal connections with local law enforcement agencies (Hrynyk et al. 2023).

Role of OCGs

Armed groups and criminal networks can force people into forestry crime activities through life threats and induce them to sabotage satellite findings or operations in order to ensure their safety. This is the case in the Democratic Republic of Congo, where people living in or near the Okapi Wildlife Reserve are compelled to work at illegal mining sites, contributing to severe deforestation and forest degradation controlled by armed groups, who are accused of killings of eco-guards and Okapi members (Kamnitzer 2024).

Legislative obstacles

The relevant improvements achieved by satellite technology in detecting forestry crime are not always accompanied by a steady prosecution of such offences. This is because of key legal and judicial obstacles, which undermine the possibility of leveraging satellites in legal proceedings.

Missing EO in international agreements

Most importantly, satellites are absent from key binding arrangements on forestry crime. Such is the case for the CITES, which is the international treaty of reference for combating deforestation. Yet, it does not mention satellites as a relevant tool to counteract such environmental crime. At the EU level, the tracking of deforestation-free products demanded by the EUDR would be impossible without satellite images, yet the use of such applications is simply recommended by the Regulation, with no legally binding character[49]. Conversely, the EU should push for a more systemic integration of satellite data into its anti-deforestation legislation. Finally, it is relevant to note that the Regulation's entry into force has been twice postponed, such that those rules are not yet applicable.

In addition, obstacles persist at the judicial level, where the impossibility for satellite imagery to clearly establish the liability of alleged illegal deforesters, and the rejection of evidence based on satellite images without field inspections, are still some of the main justifications for dismissing lawsuits (Almeida et al. 2022). What is more, courts in some jurisdictions, such as Singapore, tend to ignore satellite evidence of wood illegally transported from one country to another, also in spite of national bans on such exports and a lack of permits, as part of the hands-off approach to dealing with this crime (Butler 2015).

Operative obstacles

Operative obstacles remain a significant hindrance in the use of satellite applications against forestry crime. In several cases, the detection of illegal logging is indeed not matched by an adequate operative capacity on the part of agencies to conduct follow-up investigations in the field (Hamm, 2024), and violations often remain unpunished. This is further exacerbated when territories are hard to access, there are significant security risks or there is widespread corruption. The lack of capacity to intervene on the ground is also one of the key obstacles to fully exploit the potential of pre-emptive applications, such as RADD and FORESTER. Budget and personnel cuts to enforcement agencies may result in a reduced number of people specialised in satellite applications as well as field inspectors able to validate satellite findings (Acebes et al. 2019).

In some cases, the lack of a complete forest inventory (detailing old growth forests, secondary forests, plantations, etc.) or its scarce availability (often because of insufficient digitalisation) complicates the detection of logging in prohibited or protected areas (Fassnacht et al. 2023). This has been his-

49. European Commission website: **Implementing the EU Deforestation regulation (EUDR)**.

torically the case for old-growth forests in Sweden which, as they were lacking proper mapping and identification, have been heavily logged despite their protected status (Ahlstrom et al. 2022).

Socio-economic obstacles

Poverty and impact of crises

Positive trends in strengthening satellite applications to curb forestry crime may be undermined by combined socio-economic challenges. Among them, the COVID-19 pandemic triggered such a rampant rate of unemployment in some countries, like Kenya, that many people turned to forestry crime and poaching to make money, while health restrictions limited patrolling activities by forest rangers (Njagi 2021). Vulnerable people whose economic subsistence depends on such crimes may therefore impair satellite applications in order to avoid destitution. Similarly, households supposed to use geolocalisation systems to detect deforestation activities can try to trick them by, for instance, stating that the apps don't work in their area because of lack of signal (Colantoni 2023).

SECTORAL ANALISYS

2. ILLEGAL POLLUTION

The MV Wakashio oil spill in Mauritius. Contains modified Copernicus Sentinel data (2020), processed by ESA.

ILLEGAL POLLUTION

Numbers

AIR POLLUTION

LARGEST ENVIRONMENTAL THREAT TO HUMAN HEALTH: **7.9 MILLION** DEATH ARE ATTRIBUTED TO AIR POLLUTION

SOIL POLLUTION

AFFECTS **3.2 BILLION** PEOPLE AND THREATENS **95%** OF FOOD RODUCTION

WATER POLLUTION

80% OF WASTEWATER IS UNTREATED GLOBALLY, COSTING THE GLOBAL ECONOMY AROUND **$260 BN/YR**

Benefits

OBSERVING POLLUTION

AIR AND WATER POLLUTION IS MORE VISIBLE WITH SATELLITES THAN THROUGH HUMAN EYE.

KEY FOR LIABILITY

HISTORICAL IMAGES CAN RECONSTRUCT A SPILL'S ORIGIN AND CULPRIT.

DETERRENCE EFFECT

VESSEL OPERATORS MODIFY BEHAVIOUR KNOWING SATELLITES ARE WATCHING - MINERAL OIL SPILLS IN THE BALTIC SEA FELL FROM 763 (1989) TO JUST 32 (2024).

Obstacles

TECHNICAL

HIGH-RESOLUTION SAR IMAGES NEEDED TO DETECT MINOR SPILLS ARE SCARCE AND COSTLY. SENTINEL-1 REVISIT TIME (6-12 DAYS) LIMITS REAL-TIME RESPONSE. SOIL AND AIR POLLUTION REMAIN TECHNICALLY DIFFICULT TO DETECT.

POLITICAL

CORRUPT OFFICIALS HIDE POLLUTION EVENTS AND REJECT SATELLITE EVIDENCE. POLITICAL ELITES MAY AWARD CONTRACTS TO UNQUALIFIED OPERATORS OR INTIMIDATE ANALYSTS DELIVERING FINDINGS.

LEGAL

KEY CONVENTIONS DO NOT MANDATE SATELLITE USE. COURTS OFTEN REQUIRE AERIAL OR ON-SITE CONFIRMATION BEFORE ACCEPTING SATELLITE DATA AS EVIDENCE. FRAGMENTED NATIONAL LAWS HINDER CROSS-BORDER ENFORCEMENT.

OPERATIVE

TRANSNATIONAL SPILLS REQUIRE COORDINATION ACROSS JURISDICTIONS, BUT AGENCIES OFTEN LACK THE COMPETENCE OR RESOURCES TO OPERATE IN INTERNATIONAL WATERS.

SOCIO-ECONOMIC

STATES WITH LIMITED RESOURCES CANNOT COORDINATE SATELLITE AND AERIAL SURVEILLANCE SIMULTANEOUSLY. INTERNATIONAL COOPERATION IS UNDERMINED BY RESOURCE GAPS AND POLITICAL RELUCTANCE TO SHARE DATA ACROSS JURISDICTIONS.

2.1 OVERVIEW OF APPLICATIONS IN THE SECTOR AND RECENT EVOLUTION

Illegal pollution refers to a wide variety of environmental offenses, divided into pollution of soil (including, for instance chemical or pesticide contamination), pollution of air (covering for example gas leakages, emissions of CO_2, methane or particulate exceeding legal limits) and pollution of water (related to oil spills, illegal discharges of sewage or garbage into the sea or other bodies of water). EO observation is largely used for the third category (particularly for oil spills) and, to a lesser extent, for the second (especially for methane emissions). This is largely due to difficulties in detecting soil pollution or CO_2 emissions using the currently available missions and methodologies; this however may change in the future, particularly because of the expansion of the Sentinel missions.

Detecting oil spills is one of the most longstanding and consolidated uses of satellite data, and has been among the most frequent causes for activation of the International Charter Disaster and Space, ICDS (counting six activations for 2024 alone)[50]. The success of these applications mostly comes from the efficacy of using SAR images to detect spills on the sea (although they are proving useful on land as well) (Low et al. 2021), where they appear as high-contrast, elongated shapes on the surface. Applications are thus used to estimate the amount of oil spilled, the impact on coastal communities and on ecosystems, but also in forensic analyses to identify the vessel responsible for the spill. This is particularly useful when the spill is not detected immediately; once the oil has sunk or dispersed, it is harder to understand the actual impact of the event and track the culprit. Historic satellite images can be used to understand the dynamics of the accident. Satellite images can also be used to understand the dispersion of oil due to currents and prevent damage to fragile ecosystems (as happened, for instance, on the occasion of the BP Deepwater Horizon spill)[51]. These methodologies can be used for both major and medium spills (respectively more than 700 tonnes and between 7 and 700), as well as for minor ones (less than 7 tonnes), and for pollution events that result from, for instance, barge cleanings or other activities. It is however worth mentioning that the smaller events require higher resolution images in order to be detected (for instance those offered by providers such as ICEYE)[52]. Finally, AI is also increasingly applied for the scanning of large parts of the sea, to automatically detect pollution, leveraging on the increasing use of deep learning on SAR images (as in the platforms discussed for fishery crime, see Fishery crime). This is the case in the southern and eastern Mediterranean, where a research team from the German Aerospace Center (DLR) has recently been training an oil spill detection tool using Sentinel-1 data, aiming at developing an early warning alert system (Sentinel Online 2023).

Air pollution

Air pollution is instead a sector where the employment of satellites for environmental enforcement is still limited. This despite a widespread and consolidated use of EO to monitor pollution levels worldwide (as in the case of Copernicus' Atmosphere Monitoring Service)[53]. Indeed, such measurements are solely focused on the overall monitoring of indicators related to air quality or CO_2 concentration in specific regions, but currently this research has not identified any application used to identify or prosecute individual offenders.

Methane and other emissions

This relatively low use is changing at least for methane. From the early 2020s, the sector has been the subject of a growing discussion over the regulation of emissions due to their significant impact on the climate, which was first finalised by the EU in a 2020 Strategy (European Commission 2020) and then in a 2024 Regulation (European Parliament and Council of the EU 2024c). The latter imposes a series of penalties (which will be specified individually by EU member states), and will then require monitoring major emitters and will expect enforcement action for infringements. China is also going in the same direction following the publication of its 2023 Methane Emission Control Action Plan (Rouzi, 2023). Similar provisions were contained in a number of US legislations (the Clean Air Act and the Inflation Reduction Act in particular) (Barczewski 2023), although the current Trump administration has already partially blocked their application (Frazin 2025). In this sense, the current EO methodologies used to monitor methane emissions will likely be used in the future also for enforcement action; ESA's Sentinel-5P (with the support of Sentinel-1 and 2) is particularly effective to detect methane plumes, especially when combined with machine learning (ESA 2023). The expansion of the Sentinels mission will further increase this capacity (see **Copernicus Sentinel Expansion missions**).

2.2 MAIN PLAYERS INVOLVED

The main players involved in countering air, soil and water pollution through satellites include agencies, such as Interpol and the European Maritime Safety Agency (EMSA), at the supranational level, as well as na-

53. Copernicus website: **Air quality**.

tional authorities (enforcement agencies, as well as national research institutes and organisations, in particular). NGOs also play a significant role.

Role of Interpol

Among other activities, Interpol has a strong record of supporting environmental forensic inspectors and investigators in the acquisition of expertise and skills in pollution crime enforcement and encourages the use of satellites when developing a legal sampling strategy and selection of sampling sites (Interpol 2014). Most importantly, it coordinates pollution crime operations. In 2018, in collaboration with Europol, Interpol's Pollution Crime Working Group launched Operation 30 Days at Sea. This was the first global operation ever led to focus a law enforcement response to marine pollution in the European context, and aimed to detect marine pollution offences, including illegal discharges of oil and garbage from vessels, breaches of ship emissions regulations, and pollution on rivers and land-based runoff to the sea. The operation detected 500 offences and involved 276 law enforcement and environmental agencies, maritime and border agencies, national police forces, customs and port authorities across 58 countries. Traditional surveillance techniques and innovative technologies, including satellites, were extensively used during the operation. In particular, EMSA's CleanSeaNet and SafeSeaNet satellite systems were integrated for the first time into an International Criminal Police Organization (Interpol) operation, benefiting several countries including Denmark, Germany, Portugal and the United Kingdom. In addition, while in some countries satellite imageries were already incorporated in marine pollution enforcement, the Interpol operation triggered their use in several other states. Among others, Indonesia focused its operation on oil spill monitoring using satellite sensors, namely ESA Sentinel Image, Lapan Landsat Image, SeonSE (Smart Eyes on Seas), BARATA-BROL (Marine Research and Observation Institute station in Bali), KKP (Indonesian Ministry of Marine Affairs and Fisheries) and Bakamla's Dashboard application, while Sweden mapped mineral-oil pollution incidents through satellite imagery (GW Prime, 2022). In Pakistan, satellite imagery was instrumental in identifying the vessel responsible for a large oil spill detected during the operation, with over 40 metric tons of bunker oil dumped in the sea. Similarly, the use of satellite images allowed authorities to detect marine pollution offences in Argentina and Sweden (Interpol 2018). Germany analysed over 40 satellite pictures that, in combination with inspections and other technologies, detected 165 marine pollution offenses and triggered 37 investigations of water pollution crime and illegal shipments (GW Prime, 2022).

Role of EMSA and CleanSeaNet

As mentioned, this operation benefited significantly from EMSA's CleanSeaNet[54]. This satellite system has been developed by the EU Agency in the framework of the Directive 2005/35/EC on ship-source pollution and related penalties, which tasked EMSA to work with member states on developing technical solutions and providing technical assistance in the prevention of, and response to, pollution from ships and oil such as through tracing discharges by satellite monitoring and surveillance (EMSA 2018). Since 2007, the Agency has operated CleanSeaNet, the European satellite-based oil spill and vessel detection service. CleanSeaNet covers all European sea areas and, for a number of coastal states, is the only remote sensing tool available to detect and monitor oil spills at sea. This valuable service is based on the near real-time analysis of radar images in order to detect possible illegal discharges from ships. When a possible spill is detected, an alert is immediately sent to the relevant authorities in the coastal state. Combining radar images with information from vessel tracking systems can reveal the identity of possibly polluting vessels. In addition, CleanSeaNet is able to provide satellite images that cover more than just one coastal state. In turn, therefore, EMSA's satellites increase cooperation between neighbouring coastal states in several ways, for instance by planning satellite and aerial surveillance activities and exchanging information on pollution events. In addition to CleanSeaNet, Copernicus supports oil detection at sea in geographic areas beyond the EU, such as overseas territories of EU member states.

National authorities

National authorities are also at the forefront of pollution crime enforcement. National research institutes and organisations, in particular, are playing a key role in advancing the use of satellites in the field. Scientists are hence using satellites to identify air and water pollution caused by ships. By using data from the Copernicus Sentinel-5P satellite, scientists are now able to detect nitrogen dioxide plumes from individual ships (ESA 2020b). In addition, by drawing on nearly two decades of satellite imagery, NASA's scientists have created the first global history of measurements of ship tracks and found that the number of ship tracks fell significantly after the new International Maritime Organization (IMO) regulation limiting sulphur emissions from fuel oil in ships went into effect. NASA researchers have used advanced computing techniques, including AI, to automatically identify ship tracks across 17 years of daytime images (2003–2020) captured by NASA's MODIS aboard the Aqua satellite (Mersmann 2022). Satellites are able to detect water vapor coalescing around small particles of pollution in ship exhaust (NASA Earth Observatory 2022). The brighter the

54. EMSA CleanSeaNet satellites have played a significant role also in other operations against pollution crimes. For instance, Contracting Parties of the Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea, which aims to protect the marine environment of the Baltic Sea from all sources of pollution, have been cooperating on aerial surveillance to detect illegal discharges since the 1980. From 1988 to 2014, nine confirmed spills of oil, chemicals, sewage or garbage have been detected in the Baltic Sea by EMSA CleanSeaNet satellite (Görlitz and Interwies 2021).

marine clouds are, the more polluted they are. This means that ships are emitting more sulphur than allowed by law. Similarly, another group of scientists, from the Royal Netherlands institute of Meteorology, recently demonstrated that satellite observations can detect the impact of pollution on clouds by measuring sulphur dioxide emissions on ships passing through the western Atlantic coast of Southern Africa (Puschmann 2024). Satellite imagery has also emerged as an effective method for soil pollution detection, offering advantages in cost, accessibility and accuracy. Researchers usually rely on several satellites, especially Sentinel-2 and Landsat 8. The integration of multiple satellite datasets and advanced machine learning techniques allowed Portuguese researchers to address limitations of individual satellite systems, thereby improving the overall accuracy and depth of analysis (Nejad et al. 2025). In addition, Copernicus' Sentinel-5P satellite has been used to measure methane and is currently the only satellite instrument that produces a global map of methane concentrations every day (ESA 2023). Yet, very recently, scientists have started to combine data from Sentinel-5P with that from Sentinel-2 satellites to monitor methane emissions from space. This combination allows researchers to not only detect methane but also to localise it and quantify emissions accurately. In addition, researchers have recently found that the Sentinel-3 satellites can retrieve methane enhancements from their shortwave infrared band measurements. They can detect the largest methane leaks of at least 10 tons per hour, depending on factors like location and wind conditions, every single day. This puts these satellites in a unique position to identify and monitor methane leaks (Pandey et al. 2023).

NGOs

Finally, NGOs are increasingly employing satellites to show the impact of pollution crimes on local communities, in turn raising public awareness on pressing challenges faced by fragile communities worldwide and demanding the prosecution of perpetrators. This is the case for Amnesty International, which has used satellite images to document the impact of harmful gas flaring and oil pollution in Nigeria. First, the NGO coupled on-the-ground measurements of a single flare with the daily satellite sensor data for all flares in the Niger Delta region to determine the increased air temperatures affecting inhabitants and agricultural production within two kilometres of the flares (Amnesty International 2011a). Then, it combined satellite images from 2006, 2009 and 2011 together with witness testimonies and sampling to document the destruction of vegetation near Bodo's riverbanks caused by oil companies' illegal spillages (Amnesty International 2011b).

Although in limited cases, it is relevant to note the prominent role that courts are playing in certain jurisdictions in encouraging, or even requesting, the collection of satellite data to curb air pollution crimes. This is the case in India, whose Supreme Court has recently directed the Indian Space Research Organisation to collect data from NASA's satellite data on farm fires in northwestern India, where air pollution is becoming a severe health and human rights issue due to farmers burning crop residue in agricultural states, such as Punjab and Haryana (Sangiorgio 2025).

2.3 MAIN ADVANTAGES OF USING SATELLITES IN THE SECTOR

Traditional methodologies vs EO

Although traditional human intelligence remains relevant in counteracting pollution crimes, modern earth observation tools – such as Automatic Identification System (AIS), Vessel Monitoring System (VMS) and satellite observation through Synthetic Aperture Radar (SAR) – are of great importance to detect pollutants and to provide evidence admissible in court. What is more, satellites are more effective in the detection of pollution crimes than other technologies or methodologies. For instance, patrol boats cannot visually observe a spill over wide areas, and risk being spotted by potential polluters well before reaching pollution detection range.

By contrast, satellites provide readily available, cost-effective, accurate and wide-area maritime surveillance. At the same time, satellites can be pointed to a targeted location for monitoring specific operations in a given area. Satellites have access to remote areas, are independent of air traffic control and need no permission to fly, in comparison with traditional manned aircraft and Remotely Piloted Aircraft Systems (RPAS). In addition, satellites can monitor the spread of oil spills over a period of time.

Kinds of data

The types of satellites that are most adequate to detect pollution crimes are SAR sensors, whose technical properties allow them to gather images regardless of weather conditions and cloud cover and at any time of day or night. In comparison, optical images are less clear when there is bad weather, cloud cover and at night. Optical images are however a good option for vessel detection at sea. The combined use of aerial and all kinds of satellite information with vessel tracking systems can support the identification of potential polluters insofar as CleanSeaNet can provide evidence of the link between the vessel and the spill, while aerial and vessel information could demonstrate the identity of the vessel. Hence, satellite systems like CleanSeaNet have increased the likelihood that illegal discharges from vessels are detected in combination with other methods.

Satellites are also reported to be a pollution crime deterrent. Indeed, in 2024, only 32 harmful spills of mineral oil were detected in the Baltic Sea in comparison to the 763 pollution offences reported in 1989. Such a dramatic reduction is likely due to increased aerial surveillance and the broader use of satellite technology (HELCOM 2024). Recently, satellites have been also innovatively used to identify dark ship-to-ship transfers, addressing a crucial gap in maritime surveillance. Leveraging a combination of AIS data and PlanetScope satellite imagery, over 400 dark ship-to-ship transfers have been identified in the Kerch Strait between 2022 and September 2023, where vessels manipulated or disabled their AIS for illicit purposes (Ballinger 2024).

2.4 MAIN OBSTACLES

Technical obstacles

Availability of SAR data

Concerning water pollution, the most remarkable technical obstacle to the employment of satellites is the availability of SAR images, especially high-resolution ones able to detect smaller spills or illegal polluting practices (such as barge washing, or ship-to-ship oil transfers). The insufficient availability concerns both the geographic focus and the time coverage; Sentinel-1 data (the largest source of free SAR data) do have a global focus with specific attention to Europe, and with revisit times ranging from six to 12 days[55]. While all of the Mediterranean and the European Atlantic are included, other areas are excluded, such as some parts of the Gulf of Guinea, parts of Oceania and the Indian Ocean. Other sources are either commercial, and thus expensive to employ in investigations, or not as easily available and not as complete as Sentinel-1 (as in the case of the Capella Space open data)[56].

Technical obstacles concerning air pollution applications are harder to define, since there has not yet been use in enforcement .

Political obstacles

Satellite data provide strong evidence of water pollution due to illegal

55. ESA website: **Facts and Figures**.
56. Capella website: **Intelligence at the speed of your mission**.

discharges and are increasingly relevant in the detection of soil and air pollution. Yet, corruption is a major obstacle to satellite applications in this field. Corrupt government officials may hide the occurrence of pollution crimes for their own economic benefit and reject satellite data as a valid element of proof. For instance, despite clear satellite evidence of annual oil spills caused by crumbling facilities and foreign oil pipelines into the waters of Turkmenbashi Bay, the Turkmenistan President has signed a project to build an international and luxury resort in that area (Trilling 2013). In addition, political elites may undermine the efficacy of satellite applications by selecting contractors with no relevant expertise in managing them; experts who demand to implement or interpret satellite data may be threatened to keep them from delivering the correct results, while soil samples may be sent to laboratories that lack the necessary equipment to conduct the required tests (Radar Africa 2024).

Lack of international cooperation

In addition, given that pollution crimes, especially at sea, involve two or more states, in most cases successful enforcement will only be possible through active engagement of all parties involved within states and at the international level. International cooperation, although crucial, might be hindered by the lack of sufficient financial, human and technical resources. Additionally, on a more political level, it may be undermined by a general lack of willingness to cooperate between law enforcement of different jurisdictions. At the same time, discrepancies in the level of knowledge and usage of satellite application in the states involved may challenge the successful outcome of the collaboration.

Legislative obstacles

Satellites play a relevant role in detecting water pollution crimes, and advancements in this type of technology are making them a valuable tool also for identifying soil and air contamination offences. Yet, their application may be hindered by the lack of specific references to satellites in some key regulating frameworks[57]. For instance, the Barcelona Convention for the Protection of the Mediterranean Sea Against Pollution does not refer to satellites. At the same time, its Mediterranean strategy for the prevention of, and response to, marine pollution from ships (2022–2031) and its action plan only encourage the use of satellite imaging to deter and detect illicit discharges from ships and mention the relevance of CleanSeaNet and Copernicus services in this regard. No strong commitment or obligation to use satellites against pollution crimes is therefore put forward by this Convention and related soft-law instruments[58].

57. Similarly, satellite applications are not mentioned in the text of the Bonn Agreement for Cooperation in Dealing with Pollution of the North Sea by Oil and other Harmful Substances. Yet, satellites are recommended in the Bonn Agreement Action Plan 2019–2025 to detect, investigate, gather evidence and monitor spillage of oil and other harmful substances. Some country parties to the Bonn Agreement have adopted the use of satellite images, provided by EMSA, to provide a first alert for oil pollution rather than routine patrolling.

58. Yet, the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC), established in 1976 under the Barcelona Convention, also promotes regional cooperation to prevent marine environmental pollution by ships through the use of ESA Earth observation satellites (ESA, 2002).

Lack of reference in international treaties

Another relevant challenge is that satellite images and data documenting illegal discharges are not always accepted by courts as a stand-alone, independent source of irrefutable evidence of marine pollution (Zhang et al. 2024). Indeed, in certain legal systems satellites can only provide an initial indication of a spill, which must then be confirmed with an aircraft and on-site investigations. Satellites alone are therefore in some cases insufficient to obtain the necessary evidence for enforcement purposes.

MARPOL Convention

Finally, Contracting Parties to the International Convention for the Prevention of Pollution from Ships (MARPOL) are committed to providing for sanctions of illegal discharges. The EU has transposed MARPOL's obligations in Directive 2005/35/EC on ship-sourced pollution and related penalties. Yet, when updating the Directive in 2011 through Directive 2011/15/EC, EMSA concluded there was relevant fragmentation across the member states as national laws varied considerably in regulating the procedure for evidence collection, the evidence required, the competent courts for such cases, the amount of fines imposed, the length of the eventual imprisonment and the legal framework adopted to deal with such crimes (administrative vs. criminal law). In turn, such high level of differentiation among the member states not only undermined coordination of practices and cross-border cooperation but also hindered the harmonised implementation of satellite technologies.

Operative obstacles

Transnationality

Similarly to fishery crime, the main operative obstacle to the full employment of EO against water pollution is the transnational nature of most of the offenses, which have an impact on shores but take place in international waters. In this sense, most enforcement agencies lack either the competence to intervene or, more frequently, the capacity to operate far from the coast. The elaboration of data on water pollution also requires a significant analytical capacity that is often missing in enforcement agencies, which must then refer to external services.
The fact that satellites should be used in combination with aerial surveillance in order to be able to prosecute a pollution offence successfully also implies that aircraft need to be sent out to sea within the shortest time frame. Consequently, satellite acquisition planning and flight schedules should be coordinated to optimise the use of both satellite surveillance and aerial surveillance. However, states with limited financial, human and technical capacity may not have sufficient aerial surveillance resources dedicated to pollution control, or may lack aircraft to conduct simultaneous operations in areas detected by satellites.

SECTORAL ANALISYS

3. FISHERY CRIME

A visualisation of data from fishing vessels (dark vessels are in yellow) in the Mediterranean between Sicily and Tunisia. Credit ESA (data source: Paolo et al., 2024/Global Fishing Watch)

FISHERY CRIME

Numbers

ESTIMATED VALUE

ILLEGAL CATCHES GENERATE BETWEEN 8,9 AND 17,2 $B/YEAR. TOTAL ILLEGAL ILLICIT AMOUNTS TO 36.4 $B

HEALTH IMPACT

100.000 PEOPLE DIE EACH YEAR WHILE ENGAGING IN ILLEGAL SEA ACTIVITES (EITHER COMMERCIAL OR FISHING)

THE SCALE

1 IN EVERY 5 FISH ARE CAUGHT ILLEGALLY

Benefits

DARK VESSEL EXPOSURE

SATELLITES DETECT FISHING VESSELS THAT HAVE DELIBERATELY SWITCHED OFF AIS/VMS TRACKING.

TRANSNATIONAL REACH

SATELLITES FOLLOW VESSELS ACROSS EEZ AND INTERNATIONAL WATERS WHERE NO SINGLE COAST GUARD HAS JURISDICTION TO PATROL.

VARIETY OF TOOLS

SEVERAL PLATFORMS AND DEDICATED TOOLS CAN NOW AUTOMATE MOST ACTION.

Obstacles

TECHNICAL

●●●○○

SAR COVERAGE OF OPEN SEAS IS LIMITED. AIS AND VMS ARE NOT MANDATORY IN MANY COUNTRIES AND ARE EASILY TAMPERED WITH.

POLITICAL

●●●○○

COORDINATED INTERNATIONAL ENFORCEMENT IS STILL UNDER-DEVELOPED. SOME COUNTRIES REFUSE TO ACCEPT FOREIGN SATELLITE DATA. CORRUPT PORT AND BORDER OFFICIALS FACILITATE ILLEGAL LANDINGS DESPITE SATELLITE EVIDENCE.

OPERATIVE

●●●○○

MOST ILLEGAL FISHING OCCURS BEYOND TERRITORIAL WATERS WHERE AGENCIES LACK JURISDICTION AND CAPACITY TO INTERVENE. IDENTIFYING THE UBO OF A VESSEL REMAINS A PERSISTENT CHALLENGE.

SOCIO-ECONOMIC

●●●●○

COASTAL COMMUNITIES DEPENDENT ON FISHING MAY COVER ILLEGAL ACTIVITIES. CRIMINAL NETWORKS USE VIOLENCE AND FORCED LABOUR TO OBSTRUCT ENFORCEMENT. MANY COUNTRIES LACK TRAINED SATELLITE ANALYSTS AND RELIABLE INTERNET CONNECTIVITY.

LEGAL

●●●●●

FISHERIES CRIME LACKS A UNIFIED LEGAL DEFINITION - CLASSIFIED AS CRIMINAL OR ADMINISTRATIVE DEPENDING ON JURISDICTION. SATELLITE EVIDENCE IS SOMETIMES REJECTED OR BYPASSED VIA OUT-OF-COURT SETTLEMENTS TO AVOID PUBLIC SCRUTINY.

3.1 OVERVIEW OF APPLICATIONS IN THE SECTOR AND RECENT EVOLUTION

Fishery crime covers all offenses along the supply chain of fishery, from IUU fishing, which refers to improper fishing activities, to illegal trade of fish products, customs and tax violations, corruption and other crimes.

Satellite applications are less consolidated in this sector compared to forestry crime or illegal mining, but are gaining momentum, also thanks to the growing policy and enforcement attention dedicated to the topic worldwide in the past decade. In most cases, applications cross-reference satellite detection of vessels with the information provided by their tracking systems or highlight the presence of dark vessels without functioning tracking systems. This detection is then matched to other information (existence of protected areas in the areas of operation of the vessel, data collected from the ground or from aerial sources, for instance) to investigate potential illegal activities. The majority of cases concern IUUF, but there have been instances of satellite detection of other offenses, such as ship-to-ship transfers (i.e., when bycatch is illegally sold by trawlers to smaller vessels, which will then distribute it through local markets) (Interview 7).

Recent breakthroughs

This approach has been used in several investigations by national agencies, in some cases supported by international organisations that provided them with data or even with a full analysis of the case (Interviews 7, 16 and 17). The use of EO against fishery crime has however strongly benefitted from the development of two major platforms employing satellite data, the GFWA[59] (by Global Fishing Watch) and the Skylight platform (by Ai2)[60]. Both adopt the same approach, i.e., the use of free data sources (usually Sentinel-1, Sentinel-2 and Landsat 8-9)[61], eventually with data provided by commercial partners (in the case of Skylight Maxar and Spire), which are compared to the available tracking data (from AIS and VMS). The two platforms then automatically identify dark vessels, and offer also some personalisation and analytical tools to improve the detection of illegal activities. Unlike Skylight, Global Fishing Watch Map is open access and free to use through its online map.

3.2 MAIN PLAYERS INVOLVED

National authorities (enforcement agencies, departments of fisheries, ports and customs, law enforcement agencies and the police), NGOs and

59. Global Fishing watch website: **Map**.
60. Ai2 website: **Skylight**.
61. **Skylight** website.

international organisations such as the United Nations Office on Drugs and Crime (UNODC) are the entities that mostly harness satellites in their operations against fishery crime.

UNODC and Global Maritime Crime Programme (GMCP) organise trainings for officers of Departments of Forestry, Fisheries and the Environment, the Departments of Transport, Maritime Safety Authorities, and Border Management Authorities with the aim of fostering knowledge on the applications and advantages of using satellite imagery in combating fishery crime (UNODC 2024a). In addition, since 2015, UNODC GMCP has been closely engaging with EMSA, Cleanseanet and the Copernicus programme on satellite imagery to support maritime operations to counter crimes in the fisheries sector. Over the years, UNODC has supported developing countries in using satellite images, which provide for a reduction in resources needed compared with in-field patrolling operations (Interview 7). For instance, in 2017 UNODC GMCP advisors supported the planning of exercises, sea operations and inspections with West and Central African maritime law enforcement agencies as well as in the Caribbean. In Gambia, UNODC realised that most of the fishery crime operations were conducted in the north of the country whereas in the south at the border with Senegal there were no enforcement authorities from either country. The presence of UNODC in Gambia contributed to an analysis of actual strategic and tactical deployment of maritime assets by identifying where the fishery crime was happening in that area, where the dark vessels were and where the law enforcement agencies were actually deployed (Interview 7). In 2020, UNODC GMCP signed a partnership with Skylight, which offers satellite data that combines artificial intelligence and machine learning algorithms to identify suspicious vessel behaviour and alert authorities, and has since introduced the platform to law enforcement agencies in over 40 countries around the world. UNODC has enhanced these countries' abilities to identify and combat maritime crimes by facilitating access to a satellite vessel tracking system and providing training customised to each agency's mission and specific threats[62]. For instance, Indonesia has engaged in the partnership between UNODC and Skylight from the very beginning resulting in the country's Ministry of Marine Affairs and Fisheries' enhanced capacity and capability in maritime domain awareness and law enforcement (UNODC 2024b).

NGOs are also remarkably active in the fight against fishery crime by leveraging satellite technology, while raising public awareness on such se-

62. UNODC website: **Skylight-GMCP Partnership**.
63. Global Fishing Watch website: **Our Technology**.

NGOs

vere and until recently overlooked crime. The NGO Global Fishing Watch has created the first open-access online platform for visualisation and analysis of vessel-based human activity at sea[63]. In addition to AIS and VMS, the map uses satellite images that are able to detect vessels that have no tracking device or those whose tracking devices have been switched off to hide their location. Anyone with an internet connection can access the map to monitor global fishing activity from 2012. Users can upload their own data and download relevant data on ocean traffic. This map therefore offers unprecedented opportunities to increase transparency across the world's oceans and to support efforts against illegal fishing. Global Fishing Watch also offers an online database reporting unidentified vessels and showing concentrations of fishing activity in coastal areas. In addition to Global Fishing Watch, Skylight plays a key role in counteracting IUUF by providing AI-powered vessel detections, which result from a combination of free data sources such as Sentinel-1, Sentinel-2, Landsat 8-9 and Night Lights. Skylight is thus able to offer real-time data concerning suspicious events at sea. Other NGOs are contributing to the detection of fisheries crime. For instance, the NGO Pew Charitable Trusts has launched *Project Eyes on the Seas*, which synthesises satellite data in real time to detect suspicious fishing activity (Pew 2015a).

NGOs are also joining efforts with national authorities in order to fight against fisheries crime. For instance, the NGO Pew Charitable Trusts has partnered with Satellite Applications Catapult owned by the UK government, to pioneer a system that enables government officials and other analysts to identify and monitor IUUF. This technology merges satellite tracking and imagery data with other sources of information, such as fishing vessel databases and oceanographic data, to help monitor seas across the globe (Pew 2015b). Global Fishing Watch also provides satellite images to Costa Rica's Cocos Marine Conservation Area Monitoring, Control, and Surveillance Center, which are crucially relevant to monitor illegal fishing vessel activities in real time around Cocos Island (The Tico Times 2024).

National authorities

States are also leveraging the use of satellites to detect fishery crime both at the national level and as part of international cooperation initiatives. For instance, the US Departments of Defense and State and the U.S. Agency for International Development have been tasked to use satellite technologies, along with vessel tracking systems, aerial surveillance and radio frequency data, to combat illegal fishing by distant water fleets in the world's oceans. The US coast Guard, and the National Oceanic and Atmospheric Administration are also involved in supporting the initiative (Knipfer 2023). In 2021, Canada's federal institution Fisheries and Oceans launched a new programme in collaboration with national institutions and research centres (namely the Department of National Defence, Defence Research and Development Canada's Centre for Security Science, and Global Affairs Canada) as well as satellite companies (MDA Space, Canada's world leader in geointelligence, satellite systems, robotics and space operations technology) to provide satellite data and analysis to small island nations and coastal states in the Pacific and in Latin America where IUUF is particularly severe, to help them focus their investigations and maximise their enforcement efforts. In addition, in 2022, the US, Australia, India and Japan established an Indo-Pacific Partnership for Maritime Domain Awareness, a technology and training initiative to enhance maritime domain awareness in the Indo-Pacific region and to bring increased transparency to its critical waterways. This initiative harnesses innovative technology, such as commercial satellite radio frequency data collection, to provide partners with near real-time information on activities occurring in their maritime zones[64]. Similarly, in 2019 Norway launched the Blue Justice Initiative, aimed at assisting countries in fighting against international fisheries crime. To do so, Norway has shared AIS data from Norwegian satellites with all participating countries to conduct their own research and discover fisheries crime. The programme is managed by the Norwegian Coastal Administration and the Norwegian Space Agency (McBride 2023).

3.3 MAIN ADVANTAGES OF USING SATELLITES IN THE SECTOR

SAR data and extent of coverage

Patrolling and conducting inspections at sea can be very difficult because of the vastness of the area, the conditions at sea and the weather, as well as the lack of adequate human capacity and equipment. In addition, vessels operating illegally tend to switch off their AIS or VMS to avoid detection. While these techniques may hinder traditional human technologies, satellites are able to pinpoint fishing vessels engaging in fishery crime, regardless of when or where they do it. In addition, SAR satellites can detect vessels regardless of weather and light conditions in contrast to satellites using cameras. Hence, satellite systems allow authorities to more adequately monitor vessels that have disabled their AIS or VMS systems. Satellites can also identify ship-to-ship transfer in which fish caught illegally are moved from one vessel to another at sea. What is more, auto-

64. Australian Government website: **Indo-Pacific Partnership for Maritime Domain Awareness**.

mated algorithms can now quickly analyse large volumes of SAR data to detect vessels and let governments track illegal fishing in an unprecedented way (ADF 2023). Moreover, satellites provide more accurate data concerning the dimensions of and entities involved in fishery crime, which competent authorities can use to plan their policies and programmes. Although satellites need to be combined with other methodologies, as they do not show causality between the illegal offence and the perpetrator, they play a relevant role in providing tangible evidence of fisheries crime. Finally, satellites also play a relevant role in deterring illegal fishing activities. For instance, fishermen in Costa Rica are using satellite oceanographic information to improve catches, while mitigating impact on ecosystems and fighting against illegal fishing[65].

3.4 MAIN OBSTACLES

Technical obstacles

Need for a higher resolution

EO applications on fishery crime are mostly limited by the need for a high spatial resolution to identify even large trawlers, and by the need for high temporal frequency to detect them while performing illegal activities (for instance fishing in protected areas). Investigations thus almost entirely rely on SAR data, which are however scarcely available, particularly in some hotspots for fishery crime (Gulf of Guinea and Southeast Asia in particular). Satellite coverage of open seas is also limited.

Platforms and investigations also rely on the information provided by either the AIS or the VMS systems, which are however often missing. VMS is a system designed to monitor fishing activities, but it is not mandatory in several countries, and even where it is conditions vary depending on areas and sizes of vessels. AIS was instead not originally designed to monitor fishing, since it is mostly used to avoid collisions, and it is equally not compulsory in several countries and for smaller vessels. While more diffused than VMS, AIS is more open to tampering and offers less useful data for fishery crime investigations. As a result, some 75 per cent of total vessels operating at sea are unidentified (Paolo et al. 2024). Applications thus rely mostly on the monitoring of dark vessels, whose identification however requires extensive investigations on the ground (which are complicated or impossible when the crimes are taking place on the open sea across Exclusive Economic Zones, EEZs). Even when these data are available in several cases they

65. UNDP website: **Costa Rica Fisheries In Detail**.

are not reliable or would require further analysis; while AIS or VMS tracking data may indicate the owner of the trawler performing IUUF, this will not likely correspond to the Ultimate Beneficial Owner (UBO) of the vessels, who will likely be hidden under several layers of people and corporations (Horn and Fiore 2021).

Political and operative obstacles

Lack of awareness

Currently, a coordinated criminal law enforcement response against fishery crime is lacking, at least partially because awareness of the severity of this crime has emerged only recently. Limited knowledge on this crime therefore impairs not only adequate and coordinated enforcement responses, but also the use of satellite applications. Additionally, given that fisheries crimes are often international, affected countries should cooperate and share respective findings, including satellite data. Yet, some countries are reluctant to accept foreign satellite data, fearing they might be manipulated, and this in turn undermines the efficacy of satellites.

Another key obstacle to the use of satellites in this field is corruption. Indeed, bribed law enforcement officials and border or port guards can facilitate the smuggling of illicitly caught fish by impeding or obstructing the use of satellites for detection (UNODC 2016). Such is the case of 14 fisheries officials in South Africa found guilty of collecting bribes in exchange for transporting illegally caught fish to the US (UNODC 2011). Corrupt officials can interfere with border monitoring and vessel tracking in order to hide the passage of cargo boats illegally transporting fish. Foreign vessels engaging in fisheries crime may collaborate with corrupt port officials to keep conducting illegal operations without complying with satellite tracking laws. Port officials, who are required to inspect foreign vessels to deter and detect illegal fishing, can fail to provide information or supplementary documentation to allow foreign vessels to make use of national ports without complying with the satellite tracking laws that would reveal illicit fishing practices (Carrere 2023). Generally speaking, there is a significant mismatch between the necessity for stronger enforcement on fishery crime, and the still limited resources assigned by national governments to the issue (which is often still considered an administrative issue). The most relevant cases of fishery crime also often happen beyond territorial waters in EEZs, and thus agencies often lack the capability to operate far from the coast – this is particularly the case for smaller countries, such as Ecuador or Costa Rica (Interview 16).

Lack of compliance by operators

In addition, operators of industrial vessels can refuse to collaborate with national authorities to enable them to use satellites to monitor their activities, knowing that the countries concerned would not have then the means to check them at sea (Swan, 2004) . In addition, political connivence can also facilitate the circumvention of satellite-based legislation to legitimate illegal fishing. The case of Chinese vessels engaging in illegal fishing in other countries, including Ecuador and Peru, is emblematic in this regard. There is strong satellite evidence of Chinese-flagged vessels turning off their satellite systems in Peru's territorial waters to fish illegally (Aroni 2020). It seems that Chinese vessels succeeded in entering Peruvian ports despite violating the country's 2020 regulation requiring foreign ships using national ports to carry an extra satellite device, and in spite of satellite evidence of illegal fishing in Peruvian waters, because Chinese ships allegedly entered Peru ports for crew changes or certificate renewals – reasons that, according to the Peruvian Ministry of Production, exonerated them from complying with said regulation.

In addition, satellite technology requires experts with specific expertise; yet, many countries in Africa and Asia cannot afford to hire or train such experts. Several countries also lack key tools to make satellite analysis efficient, such as a stable and strong internet connection. Finally, private operators may decide not to use satellites despite being indicated by law, as a demonstration of lack of trust in the government or national legislation (Aroni 2020).

Legislative obstacles

Lack of legislative focus

According to UNODC, fisheries crime is "an ill-defined legal concept", as it refers to a range of illegal activities occurring across the entire value chain of the fisheries sector (UNODC 2016). Difficulties in regulating this crime at the legal level translate into difficulties in applying satellites to its detection. For instance, fisheries crimes are alternatively regulated by criminal law or administrative law or a mix between the two. The use of satellites, and the extent to which they can be employed, depends on the legal framework endorsed at the national level. As many states do not consider illegal fishing as a criminal offence, but rather see it as a fisheries management concern, organised criminal networks engage in these offences with relative impunity due both to low risk and high profits and uncoordinated, ineffective domestic and cross-border law enforcement efforts (UNODC 2016).

Satellite applications and AI tools integrate a very high level of technology, which makes it harder to determine whether they can be used in court, and indeed sometimes proving difficult to understand even for software experts (Blaha 2025). As fisheries crimes usually involve two or more countries, satellite evidence may be spread out geographically and often kept on servers in different countries or submitted through networks connecting different jurisdictions with different rules and levels of transparency. If rules are not harmonised or flexible enough, satellite applications may be rejected in legal proceedings because of conflicting norms. Finally, satellite evidence does not reach courts as the evidence of illegal fishing is so clear and evident that the perpetrators prefer to settle out of court so as to avoid time-intensive and expensive judicial procedures and limit public attention.

Socio-economic obstacles

Poverty and lack of economic alternatives

There are relevant socio-economic obstacles that may hinder satellite applications in fisheries crime. First is poverty. In several regions of the world, communities rely on fisheries as their main or only means of subsistence. Yet those areas particularly affected by climate change may experience a downturn in the fisheries sector. In addition, big fishing companies are pushing small-scale or artisanal fishers out of the market. In such contexts, people can have little alternative than to engage in illegal fishing or accept being involved in criminal networks to sustain themselves. Fragile fishing communities may therefore counteract the use of satellites in order to cover illegal activities at sea or in coastal areas (UNODC 2016). Second, criminal networks engaged in illegal fishing also have ties with violence and forced labour; life threats can induce people to collaborate with criminals and hamper the use or the findings of satellites (Okafor-Yarwood 2024).

SECTORAL ANALISYS

4. ILLEGAL MINING

Illegal mining in Bangka-Balatung Islands, in Indonesia. Contains modified Copernicus Sentinel data (2025), processed by ESA.

ILLEGAL MINING

Numbers

ESTIMATED VALUE

12-48 $B COMING FROM ILLEGAL EXTRACTION (2016)

THE CORRELATED DAMAGES

2M HA OF DEFORESTATION COMING FROM ILLEGAL MIINING IN 21ST CENTURY

GEOGRAPHICAL SCALE

85% OF THE GOLD MINES IN COLOMBIA ARE ILLEGAL

Benefits

PERMIT VERIFICATION

BY OVERLAYING CONCESSION BOUNDARIES ON SATELLITE IMAGERY, AUTHORITIES DETECT OPERATORS THAT ARE EXTRACTING BEYOND THEIR LICENSED AREA.

DISASTER FORENSICS

SATELLITE IMAGERY DOCUMENTS THE BEFORE/AFTER OF TAILINGS SPILLS AND MINING COLLAPSES.

MULTI DATA COMBINATION

APPS AND OTHER SYSTEMS ALLOW TO MERGE SAT DATA WITH DIFFERENT KINDS OF INTELLIGENCE.

Obstacles

SOCIO-ECONOMIC

ASM IS OFTEN RELATED TO ILLEGAL ACTIVITES, LOCAL COMMUNTIES TO NOT ACCEPT THE USE OF SATELLITES BEACUSE OF THIS AND CAUSE THEY SEE IT AS TOO INTRUSIVE IN THEIR LIVES.

TECHNICAL

HIGH-RESOLUTION IMAGES NEEDED FOR ASM DETECTION ARE COSTLY AND NOT ALWAYS PUBLICLY AVAILABLE. CLOUD COVER IS A MAJOR OBSTACLE IN THE AMAZON AND SOUTHEAST ASIA, WHERE MOST ILLEGAL MINING OCCURS.

LEGAL

NO BINDING INTERNATIONAL INSTRUMENT DIRECTLY ADDRESSES ILLEGAL MINING. DOMESTIC LEGISLATION RARELY MENTIONS SATELLITES AS AN ENFORCEMENT TOOL. PROSECUTORS AND JUDGES OFTEN LACK SPECIALISED KNOWLEDGE, LEADING TO FAILED TRIALS.

OPERATIVE

INACCESSIBILITY OF REMOTE MINING AREAS AND SECURITY RISKS DELAY OR PREVENT FIELD FOLLOW-UP. CONCESSION DATA IS OFTEN INCOMPLETE, UNDIGITISED OR WITHHELD. THE UBO IS ROUTINELY HIDDEN BEHIND COMPLEX CORPORATE STRUCTURES.

POLITICAL

GOVERNMENTS ARE OFTEN COMPLICIT - MINING COMPANIES FUND ELECTION CAMPAIGNS IN EXCHANGE FOR CONCESSIONS. CORRUPT OFFICIALS DENY SATELLITE EVIDENCE AND BLOCK ENFORCEMENT. IN CONFLICT ZONES, MILITIAS CONTROL MINING AREAS INACCESSIBLE TO STATE AUTHORITIES.

4.1 OVERVIEW OF APPLICATIONS IN THE SECTOR AND RECENT EVOLUTION

Illegal mining covers all offenses across the mining supply chain, from the unauthorised extraction of minerals to the illicit trade and smelting of ores. It is a common, consolidated environmental crime, which is also witnessing a global expansion due to the increased demand for critical and other minerals, due to the energy and digital transition.

Considering only extraction activities, illegal mining can be divided into two main areas: artisanal and small-scale mining (ASM) and large-scale mining (LSM). Although ASM is often informal and conducted without official permits, it is not universally illegal. In certain instances, ASM operations are situated near or even within large, established concessions. LSM is instead in most cases at least partially or formally legal, and violations stem from exceeding the concession area, the authorised environmental impact, or from illegal practices. This has recently been the case for the extensive illegal nickel mining in the Raja Ampat archipelago in Indonesia (Jong 2025a). Cases of illegal ASM are instead the well-documented illegal gold mining in the Amazon (Greenpeace International 2025), usually run by individual criminals or small organised crime groups (frequently both are associated with larger crime groups), or the illegal extraction of rare earth elements (REEs) in Myanmar, coordinated by organised crime groups and militias (Global Witness 2022).

Satellite applications play a significant role in action against illegal mining. In the case of ASM, satellites are mostly used to detect the presence of illegal mines in, for instance, protected or hard-to-access areas. Data supplied by Planet were for example largely used to identify illegal REE mines on the border between Myanmar and China by the NGO Global Witness, since the territory is almost impossible to access due to the tense political situation in the country (Global Witness 2022). UNODC instead conducts extensive scanning of the Colombian Amazon to spot illegal gold mines (Interview 6).

In the case of LSM, satellite data are instead mostly used to see if a legal operation is conducting illegal activities, which ones, and to what extent. In the case of illegal nickel mining in Indonesia, satellites were extensively used to see mining outside concession areas and illegal sediment deposits and tailings, for instance (Jong 2025b).

Applications adopt mostly optical data, with some employment also of SAR images in areas with significant cloud cover. SAR interferometry has also proved to be useful to monitor illegal mining (Maowei et al. 2011). Uses concentrate mostly in four categories:

- Scanning of the territory to check for illegal mines. This is done mostly for ASM, in some cases using AI to automate the process, and tip and cue techniques to further investigate violations by mixing low- or medium-resolution images with high-resolution ones.
- Comparing concession maps and other information to the actual impact of operations on the territory, to detect violations. The juxtaposition of concession maps on satellite images can reveal an illegal expansion of extraction activities, while images focused on tailings can reveal excessive pollution (as done, for instance, using Sentinel-2 images to detect pollution of rivers in Angola and DRC due to the Catoca mine tailings spill) (Ruppen et al. 2023). Satellite data can also be used to detect illegal or excessive water extraction, which is often a crucial component of mining activities, particularly for REEs and lithium mining.
- Checking to monitor the construction of unauthorised infrastructure (dams, basins, channels, ore deposits) or the illegal management of existing infrastructure (excessive volume of tailings contained by dams, illegal expansion of ore deposits, etc.). This has been performed by NGOs in Mexico to monitor the environmental impact of the highly polluting copper mine on the Rio Sonora (Interview 38) and by South African enforcement agencies to detect illegal coal deposits (Interview 33).
- Estimating the damage inflicted by mining disasters and helping forensic analyses to understand responsibility. While these applications are also being employed by companies to prevent mining disasters (Casey 2022), they have also been one of the earliest applications of satellite data in relation to environmental crimes, and one of the most consolidated; the estimation of damage through satellites has been one of the most frequent applications of the International Charter Space and Major Disasters, and it is consistently done on the occasion of major and minor events – one of the most notable and recent being the Jagersfontein tailings spill in South Africa, which was covered by extensive EO analysis (Torres-Cruz and O'Donovan 2023).

The systematic use of satellite monitoring, for enforcement but also pre-emptive purposes, has been expanding in recent years. Among the most relevant initiatives, since 2022 the United States Geological Survey (USGS) has deployed its satellite capability (imagery and analytical capacity) to support investigations by US and UN agencies (Lazenby 2022). In 2024, the UN also started a collaboration with the insurance technology company Value.Space to monitor risky mining activities and prevent disasters worldwide (PearTree 2024).

4.2 MAIN PLAYERS INVOLVED

Generally speaking, the investigation of illegal mining as well as the designation and competencies of agencies involved in such operations are usually dealt with at the national level. The main players involved in the fight against illegal mining are, therefore, national authorities and NGOs. International organisations such as UNODC are however increasingly involved in supporting national authorities, particularly in the Amazon (see **Case 10**).

Enforcement agencies

As for the former environmental crimes analysed, relevant authorities are police forces – which may be responsible for the detection of illegal mining and related offences or for the performance of specialised investigative functions – as well as prosecutors and judges. Latin American countries, where the vast majority of gold mining is illegal (77 per cent in Ecuador, 80 per cent in Colombia, and 80–90 per cent in Venezuela), have particularly invested in the use of satellites in their prosecution operations (Nellemann et al. 2016). In La Pampa (Peru), deforestation caused by illegal mining dropped by 92 per cent (from 173 to 14 hectares a month) since the start of Operation Mercury in 2019, which deployed 1,200 police officers, 300 soldiers and 70 prosecutors (Collyns 2023). Thanks to radar and multispectral satellite imagery collected from 2016 to 2021, national authorities were able to quantify changes in water quality, mining pond areas and deforestation in La Pampa before, during and after the operation. They found that illegal mining had caused the deforestation of at least 100,000 hectares of the Amazon between 1990 and 2020, with severe damage to the economy and health of neighbouring communities. There however some limitations, since operations effects were relatively short lived, and did not target illegal mining in some of the neighbouring areas. In Colombia, authorities have recently moved from optical satellite imagery, whose accuracy depends on weather conditions or proper illumination, and tends to fail to detect illegal activities conducted at night, to high-resolution SAR satellite data. SAR satellite data are helping Colombian prosecutors detect illegal mining continuously, regardless of lighting or atmospheric conditions (Mohanta 2021). In Africa, several countries (Kenya, Senegal, Sierra Leone, Ghana and Tanzania) launched the Africa Regional Data Cube, a platform for sharing and analysing best practices for facilitating the use of satellite imagery to, among other objectives, monitor deforestation and spot illegal mines[66]. This platform benefits from open-source satellite data provided by NASA (LandSat).

NGOs

NGOs often play a central role in identifying and fighting illegal mining operations. Administrative authorities and police forces indeed often lack sufficient capacity and specific expertise to counter such crimes, at least partially because awareness concerning the severity, breadth and impact of illegal mining has emerged rather recently. Hence, NGOs often act as a bridge between data analysis and crime identification. In other cases the work done by NGOs complements that of police officers; this has been particularly the case of NGOs in Indonesia and in Mexico, particularly concerning project Cartocritica. Generally speaking, NGOs support the detection and prosecution of illegal mining operations by using satellites, in particular optical or multispectral images, to compare the actual area of mining sites with the area licensed, as well as to identify mining sites in unreported areas. Among other remarkable examples, WWF relied on the combination of optical satellite imagery (Landsat and Sentinel-2) and radar imagery (Sentinel-1) to showcase the severe impact that artisanal and small-scale mining can have on forests in Suriname and Ghana (Kramer et al. 2023). In particular, WWF aimed to detect deforestation that was directly or indirectly linked to illegal mining, namely occurring within or beyond the mine site, hence likely associated with it. Investigative journalists also frequently used EO against illegal mining, globally; aside from investigations in Southeast Asia, this has also been recently the case of a Joseph Poliszuk investigation for ArmandoInfo.

4.3 MAIN ADVANTAGES OF USING SATELLITES IN THE SECTOR

Extent of coverage and reach of EO

Satellites can significantly contribute to fighting illegal mining and their application brings several advantages in comparison to other technologies/methods. Among others, satellites provide for high-resolution images, which offer a detailed high-quality view of vast areas, while multispectral images allow competent authorities to identify changes in vegetation cover and soil composition, which are indicative of mining activities. Satellites thus enable authorities to swiftly identify and react to illegal mining activities. Besides, satellite imagery can support enforcement agencies in detecting illegal mining sites in a much safer way, in turn avoiding or at least reducing field missions in remote or dangerous areas. In addition, if licenses on concession areas have been digitalised, satellite images can identify potential environmental breaches in legal mining operations by comparing the actual area of the mine site and the concession given to the company. Satellites can tell if the company is exceeding its permit and provide relevant information on pollution and tailings by using multispectral images. Moreover, satellites can provide relevant information concerning other environmental crimes linked to illegal mining, such as deforestation directly or indirectly caused by illegal mining, as previously mentioned in the case showcased by WWF in Suriname and Ghana (Kramer et al. 2023). Furthermore, when GPS coordinates are provided, satellite imagery not only can quickly identify the source of minerals but can also show the changes of the operation over time, whether it has expanded legally or illegally, and the impacts of mining operations on the surrounding environment (UNICRI 2025). On traceability, GPS technology plays a crucial role in curbing illegal mining and its associated transportation activities. By providing precise location data, GPS systems can track the movement of mining equipment and vehicles, ensuring they operate in accordance with the law. Competent authorities can use GPS to track transport vehicles, ensuring that mined minerals are not smuggled or transported to unauthorised locations. GPS tracking thus helps enforcement agencies intercept illegal mining operations and their supply chains.

4.4 MAIN OBSTACLES

Technical obstacles

The most common technical limitations for the use of satellite applications against illegal mining are the limited availability and cost of high-resolution images, which are often required to detect ASM, or to focus on specific activities or infrastructures within LSM that may be in violation of environmental regulations. For instance, investigations for illegal gold mining in the Amazon are often started using recognition through Sentinel-1 SAR images, but then require further analysis using high-resolution images supplied by private providers, such as Planet (Keck, 2021). Cloud cover can also represent a major obstacle when considering offenses in

66. A data cube is a groundbreaking approach to organising, analysing and storing vast quantities of satellite imagery datasets. It is an open-source framework in which data are organised geographically over a specified time period.

regions such as the Amazon or Southeast Asia, where a large share of global illegal mining takes place – some 86 per cent of gold mined in Venezuela is estimated to be illegal (Kurylo 2024), as it is 84 per cent of REEs mined in Malaysia (The Star 2024).

Political and operative obstacles

Corruption and political opposition to EO

There are a wide range of political obstacles that might interfere with the use of satellite applications in the fight against illegal mining. Among others, corruption is surely one of the biggest challenges and among the most widespread. Corruption is indeed the main enabler of illegal mining; it hinders the use of satellites to tackle crime as well as prosecution of these illegal activities. High-level corruption can indeed impede the use of satellites by making access to mining licenses and information on mining sites (size, place, boundaries, etc.) unavailable. Without this information, satellite images cannot confirm the illegality of mining operations. In addition, corrupt policymakers or high-ranked officials may hinder satellite applications by denying the relevance or accuracy of the satellite data or by hampering the creation of specific knowledge and expertise of enforcement and other competent authorities on satellites in criminal matters. In Indonesia, it is common for policymakers to accept money from mining companies to fund their election campaigns in exchange for land concessions and favourable regulations (see **Case 5**) (Jong 2023). Hence, corruption of policymakers in the country risks providing incentives to political elites to obstruct the detection of illegal mining operations through satellites, in turn perpetuating this crime. In addition, corruption undermines the effectiveness of legal frameworks on the use of satellites in criminal matters and weakens environmental crime enforcement. Moreover, low-level corruption can involve local communities, who may not divulge information about the whereabouts of illegal mining sites and actors, may impede access to the mining areas or may inform criminal networks of the inception of enforcement operations.

Another key challenge is posed by political instability in fragile countries. In contested areas or territories where the state does not have full control, illegal activities tend to proliferate as it is more difficult for the state to have full oversight on them (see **Case 2**).

Legislative obstacles

Lack of adequate legislation

There are two main legal obstacles concerning the use of satellites in the fight against illegal mining. One refers to the lack of legally binding instruments specifically and directly addressing illegal mining at the international level. Rather, the offense falls within some broader legal and normative frameworks that states must take into account, such as the UN Convention against Transnational Organized Crime and the Protocols thereto, the UN Convention against Corruption, general principles of international environmental law, and international treaties on waste management, water pollution, nature conservation and biodiversity that also contain some references to mining operations (UNODC 2022). The absence of direct, specific and explicit commitments with legal force in this area not only undermines prosecution efforts, but limits the applicability of satellites in this sector. A potential exception is the UN Economic and Social Council's 2019 resolution on combating illegal mining, which calls on states to make better use of data and "emerging technology" against these crimes (UNODC, 2020). Although not expressly mentioning satellites, the resolution refers to the promotion of solutions that can strengthen "the integrity of the precious metals supply chain, in particular as regards traceability, authentication and forensics, technology related to forensics and technology for the analysis and visualisation of big data to monitor evolving crime trends and pattern".

In addition, legal provisions on illegal mining at the domestic level rarely mention satellite applications as a relevant tool to trace, identify and tackle illegal mining, thus making enforcement less efficacious. Partially, this is because legislative frameworks against illegal mining are often outdated and do not reflect technological developments. This adds to a general lack of adequate knowledge and specialisation of prosecutors and judges in this field, which leads to failures in detecting illegal mining practices or in fully understanding the seriousness of these offenses, leading to unsuccessful trials.

Operative obstacles

The full use of satellite applications against illegal mining is also hindered by obstacles concerning the capacity to operate on the territory, the availability of documentation and the identification of the UBO.

Insufficient enforcement capacity

While satellites can often offer a clear picture of the activities on the ground, it is often complicated for enforcement agencies to follow up with timely investigations – suspicious cases are often either not investigated at all, or too late to apprehend potential offenders or limit environmental damage. This is due to a variety of causes, including the inaccessibility of the territory where mines are often located, lack of capacity and staff in enforcement agencies, and security risks. Indeed, these areas are often controlled by organised crime groups, with corruption also playing a key role in hiding illegal activities; in countries ravaged by significant political instability, illegal mines are often under the control of local militias and thus completely inaccessible for central authorities – this is, for instance the case in Myanmar and parts of the DRC.

The identification of violations can also be impeded by a lack of documentation indicating the concession areas (or reliability of data sources, such as cadastres or mining ministeries), the permitted environmental impact and usage of resources. In some countries this is a systematic issue: until 2022, in Mexico, neither companies nor governmental agencies had the obligation to publish any of this information, including the GPS location of the mine itself, which, as a consequence, was "invisible" to the general public and even the population living nearby (Interview 34)[67]. Despite a change in the legislation thanks to successful lobbying by the NGO Carto-Critica, access to crucial information remains limited, and the organisation has thus decided to autonomously collect and publish it (Interview 34). This is, however, an issue in several other countries, such as Indonesia. Without public information about concession sizes and other details, it is impossible for the civil society, autonomous researchers and other players outside enforcement agencies to identify potential violations; in some cases even the work of police forces is hampered by the low digitalisation of archives and maps and a general scarce availability of this kind of information, which in several cases is only partially or incorrectly supplied by companies to national authorities (Interviews 31 and 34, UNICRI 2025).

Identifying UBOs

Finally, similarly to cases of fishery crime, while EO can positively identify illegal mines, it may then be complicated or impossible to identify the UBO of the activity. In several cases, even major investigations have faced significant hurdles as the UBO was hidden behind layers of companies and convoluted financial flows (WWF 2026). This has been a historical issue for Colombia, which has recently created a dedicated registry for UBOs of mines (Registro Único de Beneficiarios de Finales, RUB), but which still faces limited accessibility and completeness[68]. This separation between mining operations and beneficiaries increases the need for further investigations on the ground and on different stages of the supply chain (in particular to identify shipping routes), and reduces the overall efficacy of satellite applications.

67. See **Cartocritica** Website.
68. See EITI: **Beneficial Ownership - Colombia**.

Socio-economic obstacles

Illegal mining as an economic resource

Socio-economic obstacles might hinder satellite applications in illegal mining. Indeed, local communities may hinder the successful collection of satellite data (by hiding structures or other signs of activities) or inform criminal networks of satellite-based enforcement operations because being involved in, or covering for, illegal mining operations is their only economic opportunity to support their families. Indeed, the lack of any economic alternatives, extreme poverty and life threats by criminal groups are key factors that push individuals to accept being involved in such environmental offences (Nellemann et al. 2016). This is especially so in contested areas where the state does not have control over the territory; in those cases where the state does not provide sufficient protection against criminal actors; or where policymakers are conniving with criminal networks for their own profit (Jong 2023). In addition, the use of satellites may be seen as too intrusive in people's private lives and may therefore face social challenges (Coffer 2020).

OTHER SECTORS

1. SAND MINING
2. WASTE TRAFFICKING
3. ILLEGAL CONSTRUCTION
4. WILDLIFE CRIME

El Bato reservoir in Coquimbo, Chile. Contains modified Copernicus Sentinel data (2022), processed by ESA.

SAND MINING

Definition of the offense

Sand mining is defined as the removal of primary (virgin) natural sand and mineral sand resources from the natural environment (including terrestrial, riverine, coastal or marine environment) to extract valuable minerals, metals, crushed stone, sand and gravel for subsequent processing (OECD, 2026). Sand mining is a widespread phenomenon, especially in Africa, Asia and Southeast Asia, which causes severe environmental harm ranging from loss of biodiversity to coastal erosion, from land loss to water reduction (Hernandez et al. 2021). Not only is there a lack of adequate information on sand mining, but access to data is also difficult (Sreebha and Padmalal 2011). Satellite imagery has great potential to track sand mining as well as to gather data about the amount of sand removed illegally and how it varies over time (UNEP 2014b). Yet, important challenges persist to satellite applications in this context.

Being different in methodology and on the impact of the landscape compared to most mining operations, this section has been separated from the one dedicated to mining.

1.1 OVERVIEW OF APPLICATIONS

High potential of applications

Satellite imageries can play a relevant role in the detection of illegal sand mining operations as they make available data and information that manual methods cannot provide. Satellites can indeed be used to quantify the amount of sand removed illegally as well as to identify sand mining locations. Satellites are also useful to compare mining concessions with the actual area of the mining site and to assess potential illegal zones. Satellites can be used to cover both small and wider mining sites, in turn reducing the need for in-field inspections. This technology also provides for automatic detection of sand mining activity in near-real time, in turn improving transparency and effective policymaking.

1.2 MAIN USERS

Limited current applications

The use of satellites in the fight against sand mining is still limited. This is partially due to the recent understanding of the criminal nature and the adverse effects of sand mining, which remains a highly unregulated offence. At the same time, experts' understanding of how satellite imagery can be combined with other technologies, such as deep learning methods, to detect sand mining activities remains insufficient. Finally, strong political and economic convenience is hindering law enforcement in this area, which in turn discourages the use of satellites to detect these offences. Yet, there are some preliminary and relevant practices implemented by UN agencies and national research institutes to be mentioned.

The Marine Sand Watch, launched by the United Nations Environment Programme (UNEP) in September 2023, offers an interactive map showing the movement of boats captured via a network of satellites and ground monitoring stations (UNEP 2024). It is the world's first public data platform to monitor the dredging of sand and other sediments, an offence which was severely overlooked until the programme's inception.

Opportunities highlighted by researchers

Researchers are also reaching relevant achievements in applying satellite technology to sand mining detection. One emblematic example concerns India Sand Watch, a set of open-source tools which enables the production of high-resolution, real-time maps of sand mining activity in river basins in India, where sand mining is particularly acute[69]. It relies on multi-spectral satellite imagery provided by Sentinel-2 with a resolution of 10 meters, which makes scarring and pitting (typical of sand mining) clearly identifiable (Nair 2024). Satellites are then combined with machine learning algorithms, which have been pretrained on a large amount of EO data. Among other activities, the use of satellites allows Sand Mining Watch to adopt a tailored approach to sand mining, which is highly dynamic as its location often changes depending on the season and the water levels in a river. Indeed, satellites help indicate the scope and scale of sand mining in the country concerned, and to assess the legality of sand mining activity. Developed by scholars at the UC Berkeley School of Information, this tool aims to rapidly expand and become available all over the world. While potentially effective, this is yet to be applied fully to enforcement action.

In addition, researchers are attempting to innovatively combine deep learning with satellite imagery to clarify the scale of riverine mining in affected countries. One recent research study has shown an increase in waterborne activity of vessels participating in sand mining in the Vietnamese Mekong Delta by using PlanetScope imagery from 2018 to 2021 (Smigaj et al. 2023). Similarly, researchers from the University of Singapore used Sentinel-1 imagery to detect boats between 2014 and 2022 to estimate sediment budgets and extraction in the Mekong Delta (Kumar et

69. See India Sand Watch **Website**.

al. 2023). Finally, daytime and nighttime satellite images were used by Chinese researchers to identify sand-dredging vessels to detect illicit extraction in China's fourth-largest lake (Duan et al. 2019).

1.3 ADVANTAGES

Covering vast and remote areas

High-resolution satellite images provide detailed geospatial information that can be utilised to detect and monitor illegal activities with advanced accuracy and efficiency. In-field inspections are not enough to detect illegal sand mining, especially in the case of vast, remote or dangerous areas. Manual operations cannot readily spot sand mining in a timely manner, and require relevant coordination capacity. Satellites overcome these issues. In addition, they can regularly track sand mining about every two days instead of monthly in-person checks. What is more, satellites can enable a historical analysis of past mining areas that, combined with local environmental and socio-economic data, can contribute to a better understanding of the impacts of sand mining and support policymaking. Similarly, historical data on illegal mining can provide insights into how criminal networks operate and which sand deposits are at risk of extraction.

1.4 OBSTACLES

Lack of national and international regulations

Sand extraction is not regulated at the international level, which puts the enforcement of this offence into a legal vacuum. While many countries have banned sand extraction from lakes, rivers or beaches, national legislation is often insufficient or poorly enforced due to corruption, the absence of monitoring or lack of resources to prosecute offenders (De Leeuw et al. 2010). In certain countries, in fact, illegal sand mining persists as it is often linked to organised crime, with the police on the side of the illegal miners, as in the case of India (Mahadevan 2019). In Morocco, illegal sand mining is a widespread low-risk, high-profitable industry, where criminals operate with impunity and enjoy the protection of both policymakers and military forces (Abderrahmane 2022). In such contexts, satellite applications are therefore highly discouraged to hide the occurrence of these offences.

In addition, the emergence of sand mining as a relevant environmental crime is recent in several countries, which implies the lack of (effective) enforcement legislation as well as the absence of satellite applications in this field. In addition, enforcement in this field is often feeble due to under-resourced administrations with inadequate human resources and financial capacity. Indeed, the difficulty to monitor vast areas coupled with some-times ambiguous policies means that the local authorities have little or no ability to detect and prosecute illegal sand mining (Chevallier 2014, Pereira and Ratnayake 2013) .

No boundaries on concession areas

Another relevant challenge concerns the fact that mining sites on riverbeds are exposed to the river flow, which can remove signs of mining. Often, it is unclear where to draw boundaries between a mining and a non-mining area. Even with high-resolution images available, experts disagree on how to interpret satellite data (Bohnel 2024). Although the issue of interpreta-tion may be solved through the purchase of commercial very high resol-ution satellite imagery or field visits at mining sites, these require addi-tional financial and human resources that several countries cannot dedi-cate to this issue.

WASTE TRAFFICKING

Definition of the offense

Waste trafficking, also known as the illegal trade of waste, is an extremely lucrative yet low-risk environmental crime[70]. Waste trafficking is indeed hard to detect, investigate and prosecute. Among other challenges, the adoption of different legal definitions of waste and hazardous waste, as well as unclear standards on contamination levels, has led to fragmented interpretations of waste regulations, limiting their efficacious enforcement across borders (Colantoni et al. 2022a). Legal obstacles to a sound interpretation and application of waste regulations, in addition to financial constraints, have so far hindered the integration of satellite applications in the fight against waste trafficking. Yet, satellite technology would offer relevant advantages since, in comparison to manual methods, it reduces investigation time and increases cost effectiveness in detecting illegal waste sites.

2.1 OVERVIEW OF APPLICATIONS

Applications with some technical limitations

Detecting illegal waste and waste trafficking is still costly and time-consuming, especially in large areas. Photo interpretation is still mostly used by experts, and the lack of a fully automated process contributes to making the identification and prosecution of these offences cumbersome. To achieve a higher level of automation, since the 2000s GIS and remote sensing data have been combined and proved to be particularly efficient. Such a combination was promoted by an exponential increase in the availability of satellite images, whose resolution has significantly improved over the last years. Multi-spectral images can also distinguish more easily between multi-material waste and vegetation. A research study highlighted how Landsat thermal images could be useful in the detection of buried dumps, using the heat produced by the aerobic and anaerobic processes of waste as an indicator (Gill et al. 2019). Recent studies also show that the brightness and texture of satellite images are key to distinguishing organic waste from inorganic waste through a fully automatic process (Vambol et al. 2019).

In addition, GPS tracking, which uses satellite information from the Global Navigation Satellite System network, enables the detection of the movement, location and disposal of waste, helping to identify illegal dumping and other forms of waste crime. Remote sensing platforms, including satellites, may map changes in the vegetation as well as in surface minerals due to waste crime.

70. See UNODC website - **Waste crime**.

2.2 MAIN USERS

Satellite applications to tackle waste trafficking are still sporadic. Yet, relevant examples concern UN bodies, such as the United Nations Development Programme (UNDP), NGOs and national authorities with particular reference to law enforcement authorities, border guards, environmental agencies and police officers.

UNDP

In 2021, UNDP complemented satellite imagery with artificial intelligence to detect illegal dumps in Serbia (Markovic et al. 2021). By relying on ESA's satellites, UNDP was able to obtain satellite images of the Lim river, which were then combined with official data on landfills from 2007 to 2013. High-quality satellite images of confirmed landfills were used to train a system using machine learning to identify landfills on the latest satellite imagery of the Lim river. Cloudless images from the Pléiades satellite, which were taken during the second half of 2019 at a resolution of 50cm, have also been used. Potential landfills detected through this model have been visually inspected by experts to corroborate their illegality.

NGOs

NGOs support the detection of waste trafficking mainly by developing technology based on GPS tracking devices, which can, in turn, be also used to raise public awareness about the severity of the environmental harm generated by this crime. An example is the GPS technology developed within the e-Trash Transparency Project led by the Basel Action Network. More than 400 GPS trackers were applied to pieces of discarded equipment, such as LCD monitors, desktop computers and printing devices[71]. The trackers made it possible to follow the shipment of e-waste originating in the United States, Canada, Australia and the EU, to its final destination in Asia and Africa. The trackers were programmed remotely to connect with a certain frequency to satellites to determine location. The data collected by the NGO showed that in a number of instances e-waste was exported outside of countries (ranging from 6 per cent in the EU to 40 per cent in the United States), and in some cases even to countries where an export ban applied, or a prior notification procedure was required.

National authorities

As for national authorities, there is evidence of satellites being used to tackle waste trafficking in a number of ways. For instance, the German federal police and coastguard use these technologies to track ships that have been shipped to recycling facilities and dismantled in violation of national and EU legislation. The German police use satellite images from

Copernicus to follow the route and map the stops of the ship before it is beached. When combined with open-source information, satellite images made it possible to track the ship and its origin as well as to initiate the investigation of 60 cases. In France, authorities reported a 20 per cent increase in the detection rate of illegal waste sites when applying machine learning algorithms to satellite imagery (Isarin 2024).

2.3 ADVANTAGES

Quick detection

Satellite imagery allows the detection of illegal waste sites in a cheaper and quicker manner compared to manual methods. This technology also facilitates the detection of cross-border illegal waste trafficking, illegal waste storage and dumping. Sentinel-2 seems to be particularly suitable in terms of temporal resolution, but lacks sufficiently high spatial resolution, which is essential for an operational waste detection service. Greater connectivity of satellite technology and artificial intelligence could leverage predictive analytics, integrating deep learning to improve satellite imaging and inform responses to non-compliance.

2.4 OBSTACLES

Legal, financial and technical limitations

Legal, technical and financial obstacles inhibit the integration of satellite technology in waste trafficking regulations. Although governed at the international level in the context of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes, legal clarity is persistently lacking on how, by whom and under what conditions satellites can be used. Uncertainty also refers to whether, and if so to what extent, satellites can be used as evidence in courts. In addition, major skill and knowledge gaps endure as to how to use and interpret satellite data for analytical and judicial purposes.

Digital technologies connected to satellites can also pose a financial burden to states. The development of software or the purchase of high-resolution satellite images or sensors can represent relevant costs not attainable by certain countries. Finally, although the use of GPS trackers may be a useful tool to tackle waste trafficking, they can also constitute directed surveillance, as these devices are deployed for crime detection. Legal clarity on their uses and how to deal with personal privacy still requires further review (Isarin 2024).

71. See Basel Action Network website: **e-Trash Transparency Project**.

ILLEGAL CONSTRUCTION

Definition of the offense

Challenges to the use of satellites in the sector of illegal construction begin with the definition of this crime. Indeed, there is no legal framework for this crime and none of the main international organisations with a mandate on environmental crimes (Interpol, UNEP, UNODC) provide a definition of illegal construction, nor do they deal with such offence. This vacuum discourages satellite applications as a tool to detect, investigate and prosecute illegal construction crimes. Generally speaking, the term refers to unauthorised buildings, namely buildings that have been constructed without proper permits or in breach of existing regulations, including those on sites under environmental protection, as well as buildings that have been reconstructed, or whose intended use has been changed without relevant permits. Illegal construction can therefore cause environmental damage, especially if buildings are erected in protected zones or disaster-prone areas.

3.1 OVERVIEW OF APPLICATIONS

Still rare applications

Satellites are rarely used in the illegal construction sector. Yet, some relevant practices can be mentioned. Among others, high-resolution satellites can be used to identify unlawful construction by comparing satellite images with building registry data. Satellite images can be also used to detect changes in cities over time, spotting illegal construction activities. The combination of monthly satellite image data with a resolution of 1 meter and a yearly satellite image with a resolution of 0.2 meters has proved relevant to ensure both the accuracy and the frequency of illegal construction detection (Ding et al. 2024). Deep learning methods are sometimes also applied to improve the accuracy of satellite images. In this way, users can extract housing change data, planning approval, current land use and housing information to extract suspected illegal buildings.

3.2 MAIN USERS

Role of national authorities

Main users of satellite technology to tackle illegal construction are state-led or private companies as well as national research institutes. Among other examples, the leading Estonian IT company (Datel AS) has launched, in collaboration with ESA, the Illegal Construction Detector (DICAS), a web

application that uses machine learning algorithms on satellite data to identify illegal construction activities in sparsely populated areas across Europe[72]. DICAS aims to alleviate the administrative burden on local governments and promote environmental sustainability. Data are updated every six to 12 days, depending on the location of the infrastructure[73].
In Italy, where illegal construction is increasing at an "unbearable" level (ISTAT 2023), a variety of aerial and satellite images are used for data processing of soil consumption, including Sentinel-1 and Sentinel-2 (SNPA 2024). The recent improvement in the quality and accuracy of the images allows for more precise national and regional estimates. Relevant initiatives in land cover mapping conducted by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) also include the development of methodologies for the classification of land cover based on the processing of satellite images with the aim of obtaining layers of land cover with high update frequency and high spatial resolution. A further activity concerns the integration of geo-data and machine learning tools for the automatic classification of land cover from Sentinel-2 multispectral images. This activity was preliminarily carried out in two Italian cities (Rome and Pescara), testing the effectiveness of certain deep learning algorithms on different input datasets, and showed encouraging results regarding the ability of these tools to produce mappings in a short time with good accuracy. Also in these cases, no enforcement action has followed the monitoring.

3.3 ADVANTAGES

Combination of different data

Several countries rely on human operators to find illegal construction, making the process expensive and time-consuming (Mehta et al. 2024). Conversely, an automated method that pairs satellite technology with machine learning algorithms and municipal building registry data would contribute to streamlining the identification of unlawful construction. Satellites could indeed facilitate real-time alerts, significantly enhancing the effectiveness of urban planning and law enforcement. For instance, whereas multi-temporal images are especially useful for tracking construction progress, machine learning techniques can analyse the images to identify new structures or alterations. Detected changes can be verified in official building records, flagging potentially illegal construction. In addition, satellites could monitor large areas quickly and accurately, enabling the identification of new buildings, extensions or changes in land use. Suspected illegal buildings are investigated on-site to confirm violations and take appropriate action.

72. See ESA website: **DICAS: Detection of illegal construction activity**.
73. See **Datel** website.

3.4 MAIN USERS

While satellite imagery can play a relevant role in detecting illegal construction, it suffers from some shortcomings. First, satellites alone cannot confirm the existence of an illegal construction, which must be verified through in-person checks. In addition, objects hidden under tree canopies or incomplete structures (e.g., building foundations) can be difficult to detect, requiring expert analysis. Poor image resolution can also hinder the ability of machine learning models to accurately identify illegal structures, thereby reducing the overall efficacy of surveillance systems. Addressing these limitations through improved satellite image quality and advanced analytical techniques will be essential for developing reliable automated detection systems that can support the detection and prosecution of these offences.

WILDLIFE CRIME

Definition of the offense

Wildlife crime consists in all the offenses related to the destruction, killing and trade of plants and animals. Despite this being one of the main sectors of environmental crimes, the applications of satellites have been historically complicated, and they are still, in most cases, at a project stage. This is largely due to technical difficulties, since the identification of offenses such as the illegal killing or the illegal trafficking of wildlife requires very high resolution and high frequency of images (which increases the cost and reduces the availability of data), or is simply impossible using satellite data (in the case, for instance, of the smuggling of protected species across borders, such as pangolins). A few projects are however gaining traction, and have brought results that have already supported enforcement action (see **Case 8**).

4.1 OVERVIEW OF APPLICATIONS

Satellite data are however being used against wildlife crime through specific applications focusing on the context where the crime happens, and through satellite communication. Although still at an early stage, this kind of application is rapidly expanding.

Integration of tools

In most cases, satellite images of the areas where endangered wildlife lives or migrates are analysed and integrated with data collected on the ground, to understand potential areas of risk where wildlife crime is more likely to occur. This could happen as a result of human-wildlife conflict, in zones where farming is expanding and natural ecosystems are being destroyed (an instance which is easily shown by optical and non-optical imagery revealing landscape change). Satellites can also help predict the movements and migrations of wildlife by understanding changing environmental conditions (where it has rained more, where more vegetation is available, etc.), to understand where poachers may be found. Satellite data that are employed come from a variety of sources, but mostly from Copernicus and Landsat.

Satellite-based communication is also crucial. Not only it is used to send data from GPS collars (thus improving the understanding of movements of species), but it can also relay to enforcement agencies almost real-time detection of suspicious movements or sounds collected by cameras and sensors (ESA 2021). This is, in turn, supported by the application of AI to increase the coverage and speed of detection.

4.2 MAIN USERS

Park agencies and other authorities

Main users comprise park agencies and authorities and environmental police forces, although in the majority of cases the analysis of satellite data is done by civil society or international organisations (Macleod 2024). In some cases, private companies are tasked by the latter to do the analysis, which is then transmitted by the organisation or the NGO to enforcement agencies (Interview 13). In the case of South Africa SANPark, the national parks body, has launched a project focused on the use of satellite data to predict poaching, and the analysis is being done internally by the agency. This is also because SANPark has relevant experience and familiarity with satellite tools, which are employed in relation to wildfires (Interview 33), illegal waste trafficking and illegal mining.

4.3 ADVANTAGES

Few tools available

These applications show clear advantages for the operations of rangers and enforcement agencies. Above all, they represent one of the few tools available for pre-emptive action, which is crucial for wildlife crime, as in many cases the killing or displacement of endangered species inflicts irreparable damage to their conservation. Such applications allow authorities to restrict the areas they have to monitor through traditional patrolling (also through the identification of paths, openings in fences and other access to protected areas that poachers may create). This in turn makes their work more efficient and significantly decreases costs, particularly in mountainous or simply hard-to-access areas.

4.4 OBSTACLES

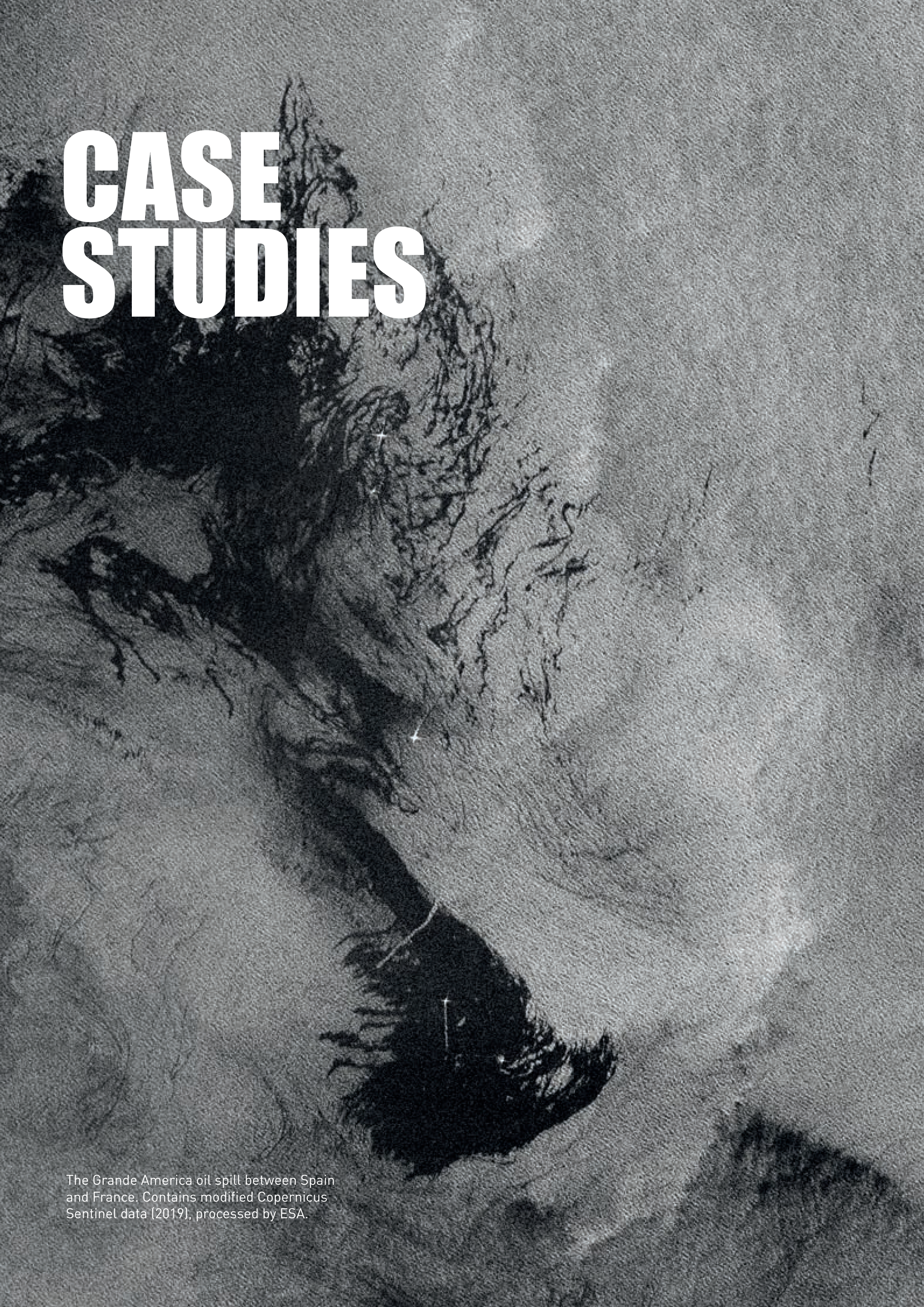
Early stage of applications

Despite all these advantages, there are still relevant obstacles for this kind of application to reach full maturity and be applied systematically. Most applications are still at an early stage and will need more testing on the ground to see if they are accurate enough to be employed, for instance, by comparing the satellite prediction with monitoring on the ground of the actual movements of herds. In most cases, it is necessary to integrate and compare very different kinds of information with satellite data, particularly human intelligence (Interview 13). This requires dedicated platforms, such as EarthRanger, but also shared and consolidated methodologies to collect and compare the data, which are still being developed and present a significant degree of heterogeneity. It will also be necessary to coordinate data collection on the ground, particularly from local communities, with satellite analysis, which is usually done by different and distant players (especially when the analysis is outsourced). It will be also harder to develop applications equally valid for different areas, considering the relevant heterogeneity among the variables considered in this analysis across regions (climate, landscape, role of communities, etc.). Finally, even when these applications reach maturity, an adequate capacity by agencies to act swiftly and effectively on the ground will be required – an issue that still troubles many applications in the illegal logging or mining sectors, for instance, and which is hampered by obstacles such as corruption, lack of specialisation, lack of budget and others.

Case studies


INDIA
Detection of illegal Mining in India: Mining Surveillance System (MSS)
BISAG-N
Illegal mining
MYANMAR
Remote monitoring of rare earth mining expansion in northern Myanmar
Guillaume de Langre
Illegal mining and environmental destruction in a conflict area, conflict minerals risk
INDONESIA
Investigations on palm-oil driven wildfires in Indonesia
Bambang Hero Saharjo
Forestry crime
INDONESIA
Illegal mining investigation in Bangka Belitung
Bambang Hero Saharjo
Illegal mining
MOZAMBIQUE
Reducing human-wildlife conflict and poaching in Sub Saharan Africa
ANAC
Wildlife crime

CASE STUDIES



The Grande America oil spill between Spain and France. Contains modified Copernicus Sentinel data (2019), processed by ESA.

1. Satellite detection of illegal deforestation and water theft in Western Mexico

Entity responsible for the analysis: El Guardián Forestal (NGO)

Enforcement actor: PROFEPA (national environmental agency), Fiscalía (public prosecutor's office) and CONAGUA (national water authority, in charge of water concessions)

Topic: Water theft, deforestation, wildfire detection

Status: Fully operational on environment monitoring and enforcement cases

Main sources of satellite data: Sentinel-1, Sentinel-2

Replicability[74]: Medium

All the information that is not otherwise cited has been provided by a representative of Guardián Forestal.

1.1 OVERVIEW

El Guardián Forestal is a Mexican non-governmental organisation (NGO) that uses Earth Observation (EO) to monitor and fight environmental crimes, primarily illegal deforestation and water theft linked to avocado production. The team has developed an interactive map, publicly accessible and very user-friendly, while a fully open-source release is under way, of an area of approximately 20 million hectares across the states of Michoacán, Jalisco, the State of Mexico, Nayarit, Morelos and Colima. Monitoring covers approximately 39,000 water reservoirs and 250,000 hectares of avocado cultivation. It is continuously updated with medium-resolution (10 m) images, mainly from Sentinel-1 and 2, but also including Landsat images.

The map shows all the areas in the region that are affected by deforestation, illegal water theft and wildfires. It does so by signalling areas affected by either water extraction, wildfires or deforestation using different colours (see image 1). To detect whether an illegal operation is taking place, the platform compares satellite images every time it receives them, based on the revisit time of the satellite. When it receives an updated picture, the algorithm compares the image with the previous one of the same area, checking if there are any signs of land clearings, for illegal deforestation, or the appearance or anomalous refilling of agricultural water reservoirs, for water theft. The algorithm has a remarkable field-validated precision of 84-92 per cent for deforestation detections and of 96 per cent for water-related detections, and was built using years of prior images of the regions to identify and map seasonal changes and to understand all the variations that could affect detection rates.

For water theft, instead, the platform builds a time series of the water surface of each reservoir from Sentinel-2 imagery and contrasts it with observed rainfall and evaporative demand. As an explicative example, during the dry season, an increase or persistence of the water surface, which cannot be explained by rain, implies external input, typically pumping from wells. A physical plausibility test complements the time series, verifying whether there are any plausible solutions that could naturally explain the filling of the reservoir. Importantly, the algorithm detects pumping, not illegality: the legal qualification arises exclusively from cross-checking flagged reservoirs against the public registry of water concessions (REPDA), and reservoirs with no matching concession are prioritised for field inspection. The whole processing chain runs on free and open data and is fully reproducible, a key feature for its evidentiary use.

After the algorithm automatically checks and evaluates the changes, it creates an alert on the map and informs the local authorities directly. The unprecedented aspect of this application is how the authorities are informed of an infraction. El Guardián Forestal automatically generates a legal complaint, which includes the municipality, the affected hectares, before-and-after photos and a QR code linking to the Global Positioning System (GPS) location. The information is sent digitally and instantaneously to the authorities. These automated complaints are now submitted as formal geospatial expert reports, a format accepted by federal authorities such as the Attorney General's Office (FGR), which reduces the room for discretion and corruption in the handling of evidence. The team of Guardián Forestal has worked with the Michoacán State Attorney General's Office (FGE) to create a training and certification programme for a certified group of experts[75]. Now, the imagery is not presented simply as evidence, but as a formal technical report. Over 1,000 complaints have been generated, and approximately half have already resulted in enforcement action, with investigation files open against the culprit. This can also be seen on the map; areas where an investigation file (*carpeta de investigación*) was opened by the Fiscalía are marked as *carpeta abierta*, or open case (see image 2).

The most interesting part of this application is the commercial enforcement mechanism. The large regions covered and monitored by the application produce more avocados than any other in the world. This system of monitoring also serves thus as a mechanism of certification of sustainability. El Guardián Forestal monitors the

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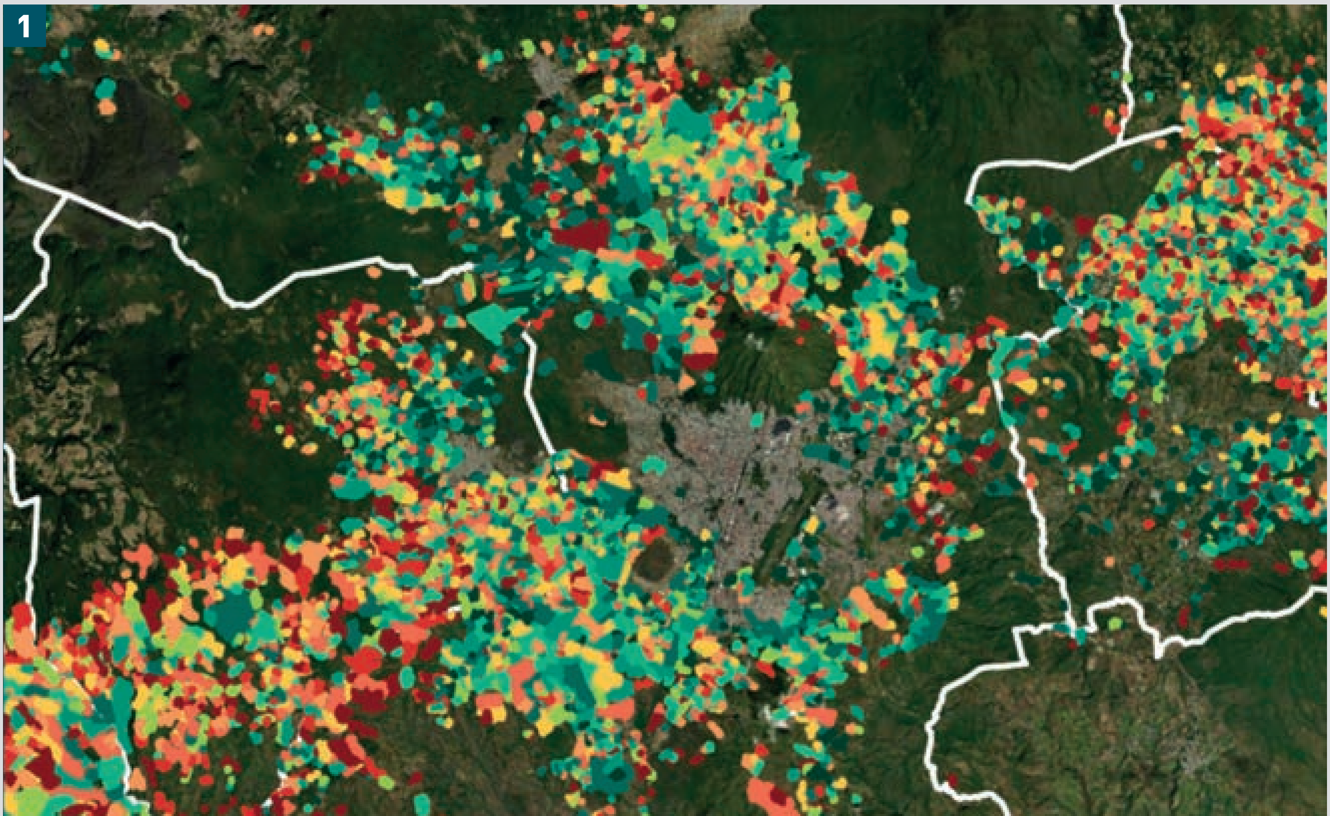
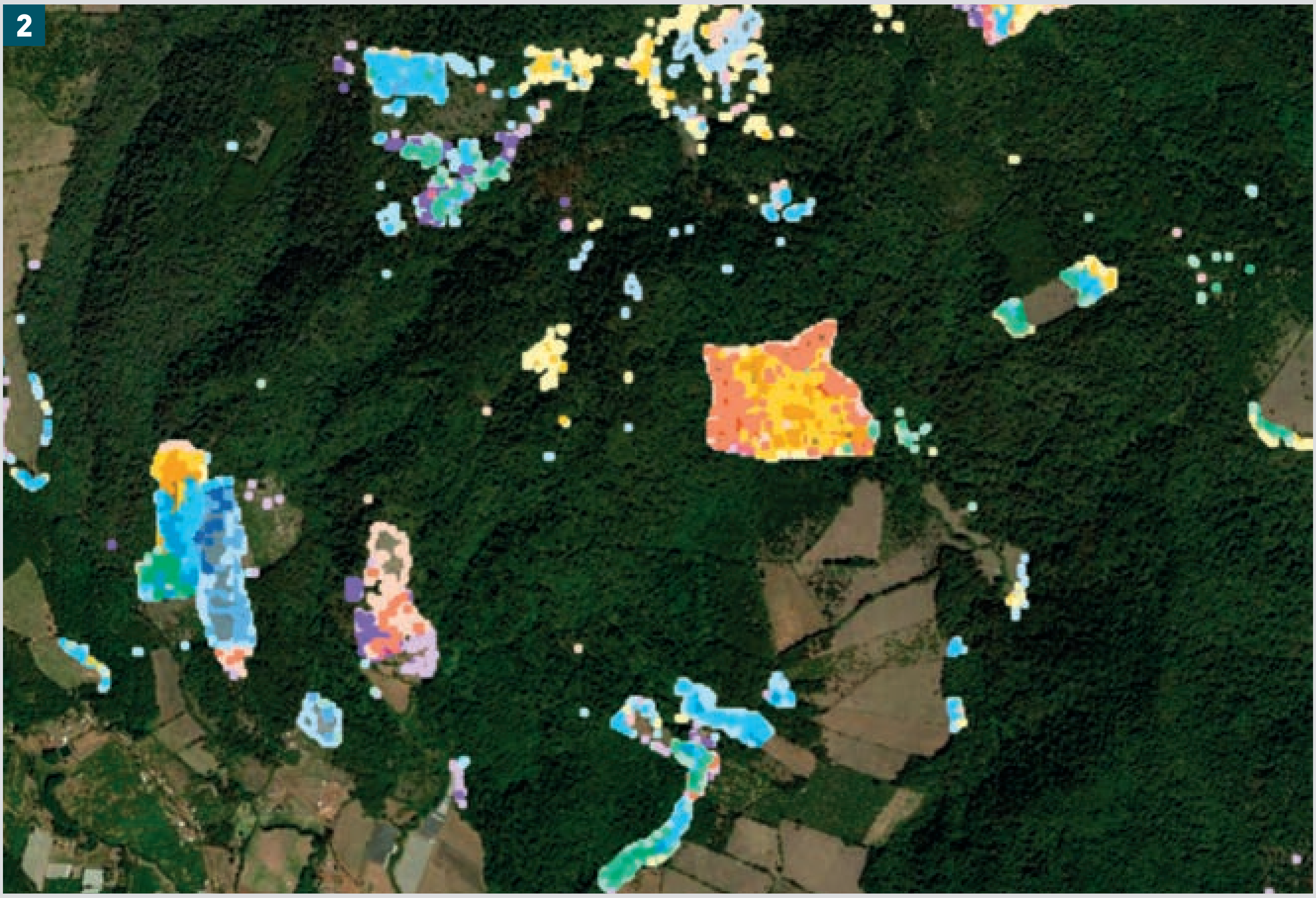


Two images from El Guardián Forestal, showing areas indicating water reserves and possible deforestation (respectively blue and red). Credit: El Guardián Forestal



situation in the area with every new satellite pass (approximately every five days), and all the avocado producers that are not flagged by the system have a "green status" in terms of the sustainability of their avocado orchards. The platform can be used by anyone to check the status of any producer in real time, ensuring that avocado production does not endanger the environment. This has also resulted in the employment of the platform by several certification entities in Mexico and in the US (see below).

1.2 BENEFITS

El Guardián Forestal creates several advantages compared to traditional law enforcement and monitoring.

Firstly, it provides continuous and reliable supervision of a very extensive area, complementing lengthy and prolonged police work in the field, reducing the time for monitoring environmental crimes. Additionally, it generates automatic legal complaints, removing the burden from individuals themselves to file complaints, which are usually long bureaucratic procedures. It also allows for monitoring of a territory where the heavy presence of organised crime groups (OCGs) makes inspections complicated and often risky for officers.

The material outcomes of using the application are particularly innovative. The complaints filed and generated indeed have consequences already in the short term, since they actively stop the export of avocados produced through deforestation or illegal water extraction. Indeed, the certification system is used not only by third parties to monitor the situation, but also by retailers and packaging houses, which do not accept any avocados from producers that are flagged by El Guardián Forestal, essentially compelling producers to adhere to environmental regulations. This practice is a game-changer in the sector, and has been able to succeed thanks to a court proceeding in the US, where four large avocado import companies were sued for making false claims on the origin of their avocados (Kaminski 2025). The companies settled and agreed to prove the sustainability of the avocados they import, and to do so, they rely on El Guardián Forestal. Several supermarkets in the US, such as Walmart and Costco, are now demanding that the packaging houses in Mexico prove to them that the avocados they buy from producers are certified by El Guardián Forestal. This has resulted in approximately 3,000 orchards blocked for export, and 92 per cent of avocado exports covered by the system.

It is also worth noting that this application shares several features with other, mainstream uses of EO against deforestation, particularly the World Resources Institute's (WRI) Global Nature Watch. However, El Guardián decided to develop a new system because of the need for more accuracy – Global Nature Watch's detections on Mexico's territory proved too imprecise for enforcement action – and also to allow for a better integration with regional and national legislation. El Guardián also required a wider system, able to detect water usage, to directly connect to enforcement action, and to provide a framework for certified trade of agricultural products – all items that are missing on other platforms.

1.3 OBSTACLES AND LIMITATIONS

To implement this type of application, there were several limitations to be addressed; some were fully addressed, some were partially addressed and some are still an issue.

The main initial obstacles were the slow bureaucratisation of legal complaints and the lack of transparency in police work, as police were often bribed by the avocado producers to not oversee the territory. These two issues were both overcome by creating the digitalised and automatic complaints generation, and by cross-checking the truthfulness of police work through satellite images. If a police officer takes a bribe, not signalling the infringements, this will be cross-checked by satellite images; the system thus creates a clear incentive against corruption, as it may be easily detected.

Differently, an issue that is still relevant is the number of complaints that are sent to the police force. As they have received over a thousand in just a few years of application, local and national Mexican police forces are overwhelmed by the volume and do not have adequate capacity to act. As a consequence, there is still a significant delay between detection and physical inspection by the police. However, the system is also producing a deterrence effect and a decrease in violations, which may amplify in the future and reduce the burden on police forces.

A persistent issue remains legal proceedings, which are still slow – it might take years to see any concrete outcomes from investigations. There is a general sense of mistrust and lack of awareness concerning EO among institutional actors, and the automated process of forming evidence often raises questions and provides common counterarguments in legal contexts. The burden of proof remains high also in this case; courts demand a chain of custody, reproducible methodology and processing traceability. Additionally, in many regional regulatory frameworks in Mexico, EO is not explicitly recognised as a primary form of evidence, creating interpretive challenges and requiring additional expert testimony.

Nonetheless, an excellent step in the right direction to stop deforestation has been taken by the state of Michoacán, which has changed the notarial law concerning private property sales[76]. In fact, now, unlike before the law passed, if a buyer purchases a property where there were acts of deforestation, they become legally responsible for the historical damage. This was a major fix in a complex loophole that prevented those responsible for deforestation from taking any accountability.

1.4 REPLICABILITY

The replicability has been evaluated as medium, since it is possible to use a similar application in other parts of the world, but fine-tuning and adaptation efforts are needed.

Regarding the replicability of the system, this will require some adaptation as it was designed specifically for the environmental conditions of Western Mexico. The supply chain certification model can also be replicated, but it would need to be adapted to different criteria established in other countries for certifying agricultural goods. This could however be expanded to several other commodities with high impact on forests, water resources or landscape, such as cocoa in West Africa or coffee in Latin America. Considering the growing global interest in tracing agricultural production, this could mark a rapid expansion of this application.

74. Replicability refers to the potential to use the same methodology as in the case study in different parts of the world. The higher the replicability the easier is to export the case study to other environments.
75. El Guardián Forestal is the only organisation in Mexico with this formal capacity with the authorities. At the federal level, the FGR has already used 15 of these reports (Information updated as of July 2026).
76. Michoacán State Congress Website: Comunicado 1107/2025.

2. Remote monitoring of rare earth mining expansion in northern Myanmar

Entity responsible for the analysis: Guillaume de Langre (independent consultant)

Enforcement actor: Not disclosed

Topic: Illegal mining and environmental destruction in a conflict area (Kachin/Shan); conflict mineral risks

Status: Operational monitoring solution implemented by the client

Main sources of satellite data: Sentinel-1, Sentinel-2, Sentinel-5P products, private providers

Replicability: High

All the information that is not otherwise cited has been provided by Guillaume de Langre.

2.1 OVERVIEW

While Myanmar has been historically plagued by various instances of illegal mining, the February 2021 coup dramatically halted the slow but steady improvements the country had been implementing in the previous decade. The significant endowment of critical minerals (particularly rare earth elements), the growing demand for such commodities due to the energy and digital transition, as well as the geographical proximity of China triggered a new, unprecedented wave of illegal mining, with substantial consequences on the environment, particularly on water resources, and on the health of communities near the mines (Fishbain and Naw 2025).

This application was devised by the independent consultant Guillaume de Langre following a direct request by a European non-profit organisation to investigate the matter. The client needed an independent way to monitor suspected illegal expansion of heavy rare earth mining and smuggling in northern Myanmar. This was happening in the northern Kachin and Shan states, areas which are inaccessible to outside observers due to active fighting between the military junta and ethnic armed organisations. The core investigative problem was not only to detect the mines, but also to understand whether EO could generate repeatable, adversarially robust evidence packages that withstand scrutiny and can be linked to supply-chain and financial analysis, while acknowledging uncertainty.

The client's questions were operational and time-bound: scale, nature, temporal evolution of illegal operations, as well as linkage to political/financial flows, with an explicit need to understand the levels of uncertainty related to these findings.

The monitoring therefore prioritised "high-value outputs" beyond the simple detection of mines, such as:

- Operational activity: Cadence of expansion, active vs. dormant phases, new access roads and processing-water signals.
- Impact quantification: Disturbed area, river turbidity/plume persistence proxies, slope failure risk windows, tailings/volume proxies where feasible.
- Attribution support (indirect): Infrastructure and logistics corridors connecting extraction zones to processors/exporters (roads, staging areas, border-route continuity).

1

Illegal mining for rare earths on the border between Myanmar and China respectively in January 2017 (first image) and December 2024 (second image). Contains modified Copernicus Sentinel data , (2017, 2024), processed by ESA.

- Repeatability & auditability: The ability to reproduce the same evidence stack at the previous points.

The innovation of the application's methodology did not lie in a single model, but in an operational design that turns multi-sensor EO into standardised, updateable evidence bundles usable by investigators and analysts (including those focused on corporate/financial mapping).

For rare earth mining in Kachin and Shan, the workflow leveraged the fact that certain extraction methods have distinct geometry visible from space. A key example is in-situ leaching infrastructure: clustered light-blue precipitation ponds.

Rather than outputting "probable mine", the system generated "prosecutor-relevant change products" highlighting:

- First appearance dates for new extraction features.
- Sustained activity windows (versus brief disturbances).
- Absence of abandonment/rehabilitation signals where relevant.

This directly addresses the key questions "what changed, when and for how long", which is closer to evidentiary needs than conventional land-cover maps.

Operationally, northern Myanmar's cloud/monsoon constraints make purely optical monitoring complicated. A simple change detection script was applied to Synthetic Aperture Radar (SAR) data to detect the appearance of new trails around mining sites and leaching plants.

Since mines have short lifespans in this area, it was important to know which sites were active and which ones had been abandoned. Sentinel-5P's NO_2 and CH_4 products were used in combination with a nighttime radiance product to measure the likelihood of activity at the mine site. HR optical imagery was treated as a verification layer: used to confirm high-confidence alerts, classify site features and generate "before/after" exhibits.

A key design choice was to deploy machine learning (ML) on occasions where it could significantly reduce analyst burden without creating a black box – i.e., a stack of evidence directly resulting from unknown algorithm elaborations, which could not be accepted in court (see Obstacles). In some cases, human verification for evidentiary outputs was applied.

Due to the fragile political situation in Myanmar and the lack of environmental enforcement across the country, this application did not result in immediate action by enforcement agencies. However, such results could be applied in future investigations, and have been extensively used to raise global awareness on the supply chain of critical minerals and their frequent illegal sourcing.

2.2 BENEFITS

This application presented a number of direct benefits, which are particularly relevant for a case which is at the same time of very high impact, of international relevance, but also presents severe complications in terms of security and accessibility.

First, the applications shows that independent EO monitoring works well also when access and registries fail. EO can confirm extraction/processing footprints where permits, audits and company registries are inaccessible or unreliable. This is a foundational advantage in conflict settings where formal data sources are missing or adversarial.

Furthermore, "red-flag triggers" integrate well with investigative workflows. EO outputs were shaped as due-diligence and investigative triggers – e.g., new pits, rapid expansion and

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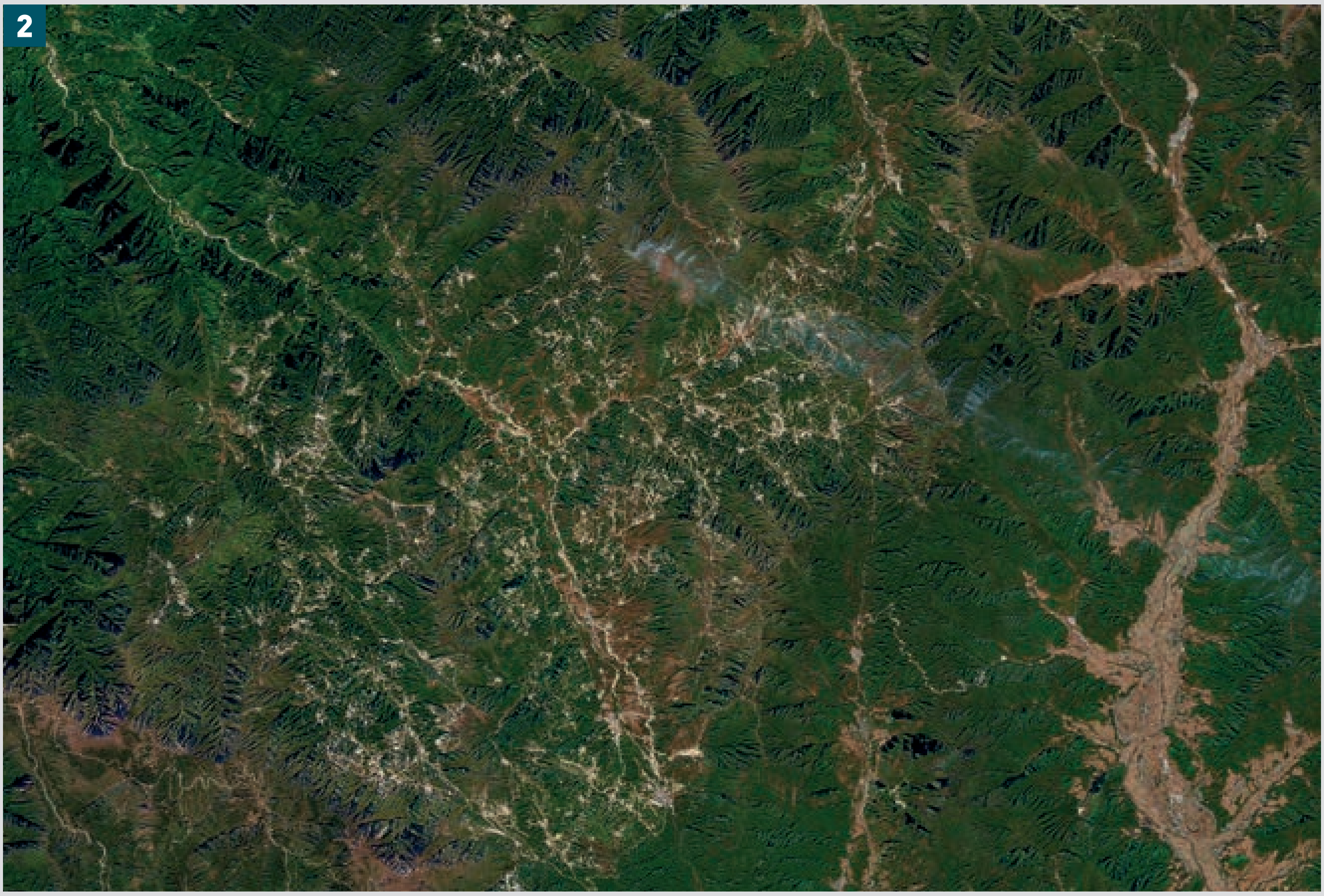

proximity to waterways/settlements – rather than as EO-only products. This makes EO comparable to financial stakeholder mapping: it becomes an input into a broader investigative graph rather than a stand-alone map.

Linking extraction to corridors and cross-border dynamics has also proved particularly effective. For conflict minerals (tin, tungsten and tantalum, the so-called "3T", and gold in particular), EO can expose not only extraction but also trade-corridor logic – transport infrastructure linking sites to border crossings and processing. This is central to enforcement cases that require demonstrating plausible pathways from mine to market.

2.3 OBSTACLES AND LIMITATIONS

Despite technical feasibility, the adoption of this application is bottlenecked by operational usability. Above all, the current political situation in Myanmar impedes the use of the applications' results in enforcement action by national authorities, which have limited control over the territory, particularly in the areas where mineral extraction is taking place (UN City 2026). As the situation in the country remains critical at the time of writing, it is not clear when this will be possible.

The information gathered remains however vital to understand the impact of illegal mining in the region, also for future remedial action, as well as to monitor spillovers in nearby countries – this is an issue that, for instance, is already affecting Thailand (Mongabay 2025). The monitoring resulting from de Langre's application has been used to raise awareness on the illegal sourcing of critical minerals from Myanmar, and its risks in terms of environmental damage, health, as well as the security of supply; in the next future, it could also be applied to try and limit the trade of illegal minerals by acting on the demand side (which may be discouraged from buying illegal commodities if their origin is exposed). However, this is unlikely at least in the short term, due to the limited choices for diversification of supply by buyers, the growing strategic relevance of these minerals for players such as China, the US and the European Union, and the still limited interest of international buyers in the sustainable sourcing of minerals.

2.4 REPLICABILITY

This approach is highly replicable because it is built on globally available Sentinel data and on transferable investigative outputs. In particular it relies on:

- **Transferable signatures and products**. Rare-earth in-situ leaching patterns (pond clusters + slope networks), road/logistics expansion and persistent disturbance are not Myanmar-specific phenomena; they generalise to other high-risk mining frontiers. Illegal mining of critical minerals is also a growing issue in Southeast Asia (particularly in Vietnam and Cambodia) and other regions, so detection methods are already required across countries.
- **A replicable evidence pipeline**. The application has developed a Detect → Contextualise → Quantify harm → Package evidence structure that proved effective in this case, but is also a generic template for environmental crime investigations, independent of commodity or geography, that can be thus easily replicated.
- **A practical civil society/international organisations use case model**. The application has also developed a structure for the sharing of information with the client, based on four steps: confirm footprints, track impacts, trigger red flags and produce time-stamped exhibits. This has proved effective for communication between the consultant respon-

sible for the EO analysis and the NGO requesting the analysis, but it could be an efficient blueprint also in other cases involving civil society or international organisations, par- ticularly for issues regarding illegal mining, illegal logging roads, unlicensed quarrying and waste-related harms.

3. Investigations on palm-oil-driven wildfires in Indonesia

Entity responsible for the analysis: Prof. Bambang Hero Saharjo, IPB University (academia)
Enforcement actor: Ministry of Forestry and Environment
Topic: Forestry crime
Status: Used in active and concluded cases, used as evidence in court
Main sources of satellite data: Sentinel-1, Sentinel-2
Replicability: High

All the information that is not otherwise cited has been provided by Prof. Bambang Hero Saharjo.

3.1 OVERVIEW

Wildfires triggered by the expansion of palm oil production have been one of the major environmental crimes affecting Indonesia in the past two decades. While fires spiked in 2015–2016, the issue is seeing a resurgence in recent years, with record hotspots detected again in 2023 and in 2025 (Jong 2025). Wildfires are usually triggered by companies owning large-scale plantations of oil palms, in order to clear the land more rapidly from natural forests, and to change the soil PH of peatland to be more favourable for oil palm cultivation. The issue affects mostly South Sumatra, and Central and South Kalimantan, where most oil palm plantations are located, and where some of the last remaining primary forest in Indonesia is located (largely in Kalimantan). Wildfires have a significant, multifaceted impact on Indonesia, and even on neighbouring countries: not only do they represent a major cause of deforestation, as up to 2.13 million hectares have been burned in 2023 alone (Oneill 2024), but they also generate serious amounts of smoke that frequently reaches Malaysia and has triggered several diplomatic complaints (Jong 2023). Uncontrolled deforestation also increases soil erosion, contaminates water sources and represents a direct threat to the safety and the health of nearby and even distant communities.

EO has been one of the most consolidated, successful and common tools to counteract wildfires in Indonesia, particularly since 2015–2023; the new endowment of data thanks to the Sentinel mission, more public attention to the issue after critical years, and changes in national legislation regarding the burden of proof for wildfire cases have allowed for a greater employment of satellite data in the monitoring of fires, and in forensic analysis for investigations (Colantoni and Sangiorgio 2024).

Generally speaking, EO is employed in Indonesia against wildfires by a variety of players, and on a variety of occasions. For example, local NGOs in Sumatra and in Kalimantan such as Jikalahari and Titian have Geographic Information System (GIS) experts who use ESA's Global Wildfire Information System (GWIS) and the National Aeronautics and Space Administration's (NASA) Fire Information for Resource Management System (FIRMS) to discover active fires, evaluate through open-source intelligence (OSINT) and use their local network to investigate the most relevant ones. They then collect evidence using mostly commercial drones.

The most complex applications are however performed by expert witnesses working for the Indonesian national police, and usually belonging to academia. This is particularly the case for Prof. Bambang Hero Saharjo, part of the IPB University and one of the most advanced and involved users of EO against wildfires for forensic analysis. Satellite data are employed in a number of ways, and to collect a number of different sorts of information; generally speaking, EO investigations on wildfires aim at understanding ecological damage (in terms of biodiversity, but also soil damage, water storage and carbon release, for instance), economic damage (replanting of the landscape and maintenance of new forests, loss of profits by communities and land owners) and restoration costs (revegetation, restoration costs and hydrological system repair costs in particular).

The methodology presented in this case study was applied by Prof. Bambang Saharjo on a major fire in South Kalimantan in August 2025. The total area affected was 1,514.9 hectares in three different locations, and it is alleged the fire was triggered by palm oil company PT SSM in an area it owns, and which it is partially authorised to cultivate (AntaraNews 2025). This methodology is however a standard approach that is systematically applied for such cases, and is based on a few crucial steps:

- **Preparatory actions**: Obtaining the concession maps to see how much of the fire happened inside the company's area, and how much it extended beyond this. Sentinel-2 imagery is then overlayed on the concession map and on the location of detected hotspots to calculate the area of fires.
- **EO analysis**: The expert witness then proceeds to analyse the imagery to detect possible evidence related to the cause of the fire, or to other criminal actions: preparatory activities, such as the opening of water channels to prevent the fire spreading towards agricultural land or selective cutting of valuable

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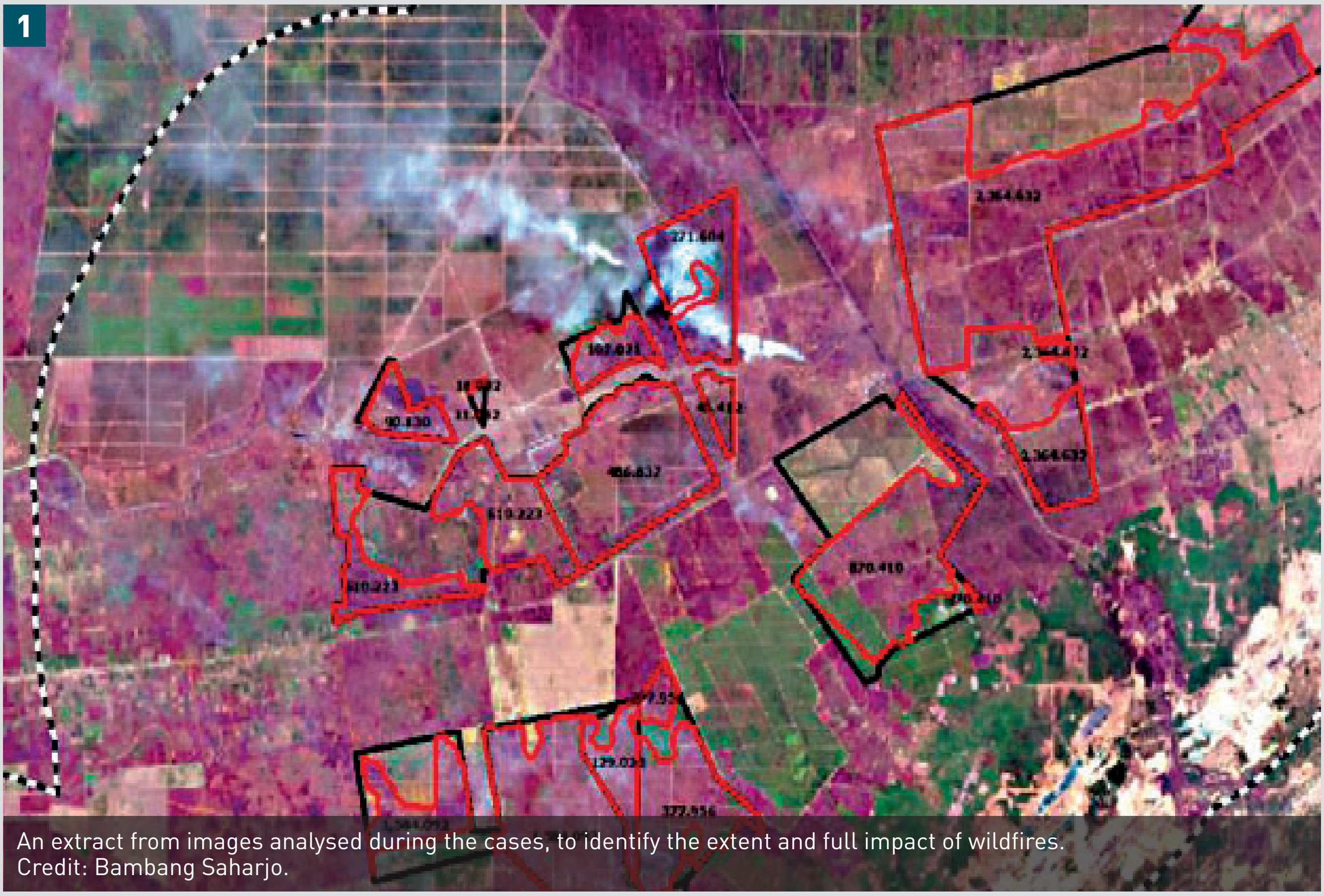

An extract from images analysed during the cases, to identify the extent and full impact of wildfires.
Credit: Bambang Saharjo.

species inside the forest, for instance; or where the fire has originated (inside the concession block or outside).

- **Evaluation**: Environmental damages are then calculated to understand the amount of biomass that has been burned, the ecological value of the area before and after the fire, and the damage inflicted to critical landscape elements such as rivers or water reserves. If the area was peatland also the ground water level is measured, since it if falls under a threshold (40 cm) this may indicate significant damage to the soil.
- **Work on the ground**: The expert witness performs then checks on the ground, also to see if fire control infrastructures were in place and if they were used.

The expert witness consolidates all information in a standard report, which is then transmitted to enforcement authorities (usually the General Attorney's office).

3.2 BENEFITS

Benefits of using EO against wildfires in Indonesia are well known, as the application is among the most consolidated. Generally speaking, they can be summarised in terms of accessibility of the territory, relevance of time series and information provided by the imagery in terms of damage evaluation and forensic analysis.

Oil palm plantations and the company's concessions in general are frequently hard to access and monitor; this is in some cases due to the structure of the Indonesian landscape, but on most occasions companies actively impede entry into the area, or even nearby. Most fires are indeed detected using the GWIS and FIRMS systems, and this also happened in the case detailed in Image X: it was spotted using satellite data, followed by an inspection on the ground by police officers. This is particularly relevant for NGOs, whose work is crucial as they provide key evi-

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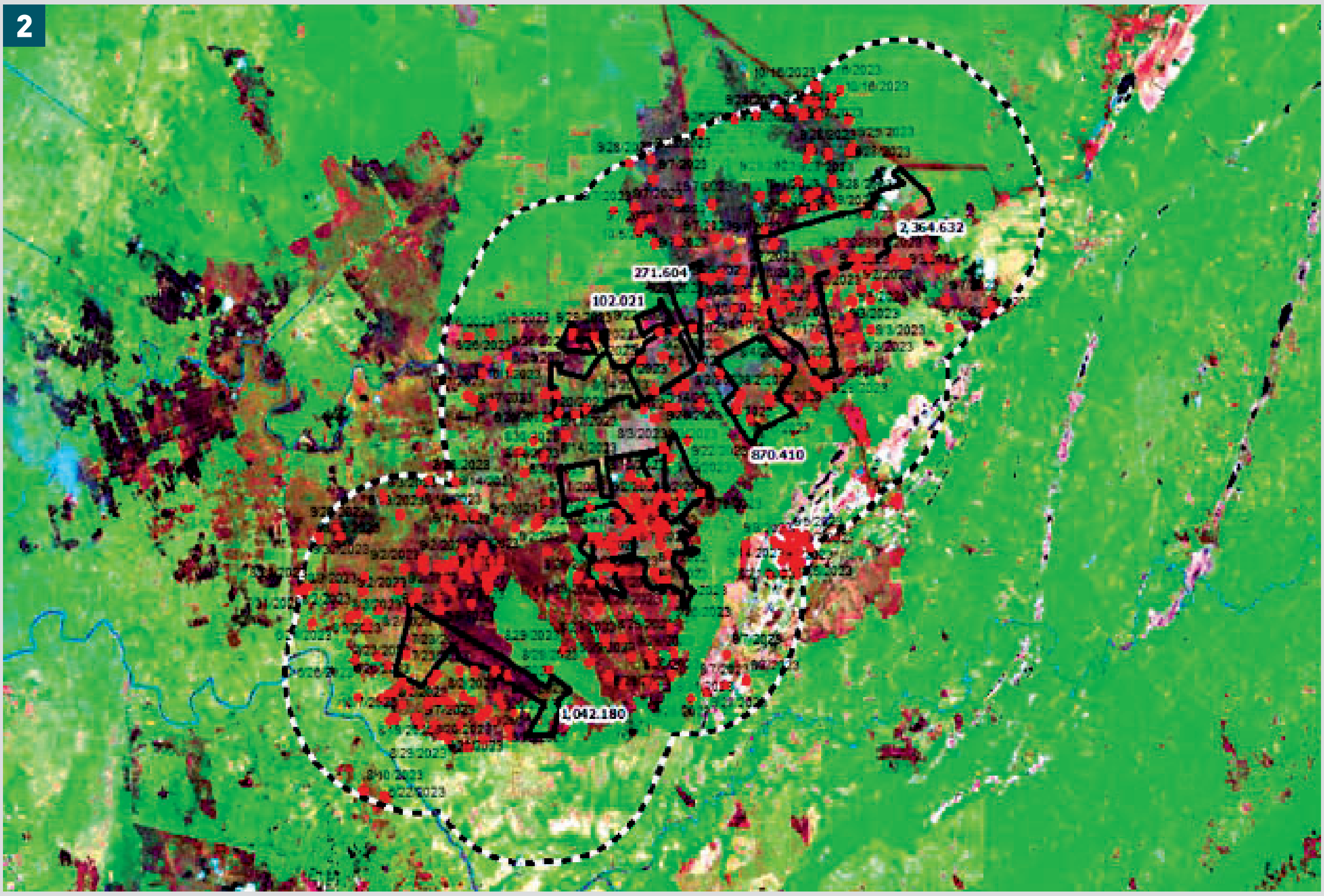

dence for cases where enforcement agencies are not taking action, but which are frequently obstructed by companies when collecting evidence.

Time series are also key to this application. While the five-day revisit time of Sentinel-2 does not provide data in most cases for the exact moment the fire started, it is enough to detect preparatory actions (which take place in the weeks and even months before the fire). These data also provide a baseline that is crucial to understand the impact of the fire, and to perform an accurate estimation of damages. Evidence is also frequently hidden by perpetrators shortly after the fire and before inspections; there have been instances of offenders even hiding the burned ground under a fresh layer of soil using heavy machinery. Satellite historic data instead allow in most cases to have a clear picture of the situation before such (often time-consuming) actions to mask the fire can take place.

Finally, EO provides an amount of data which could scarcely be obtained through traditional methodologies. For instance, Sentinel-2 data allow for the estimation of biomass before the fire that is in turn employed to understand the ecological damage. The comparison of concession maps and fire areas is used to see if there is a connection between the two – usually wildfires occurring mostly or even exactly within the concession map are triggered by the concession's owners, as they try to avoid damage to land owned by other companies.

3.3 OBSTACLES

The main obstacle to the adoption of EO against wildfires is the persistent cloud cover that frequently affects Indonesia, and which reduces the imagery available for analysis. The possibility to detect changes over relatively long times series reduces however the impact of this issue when compared to other offenses that require detections on specific dates (as in the case of fishery crime, for instance).

Action against wildfires has however been frequently hindered in Indonesia for political and economic reasons, and EO has been also targeted. The Indonesian government has a consistent history of contradicting and denying the estimates of total areas burned provided by researchers and NGOs – the official statistic for the 2023 fires is almost half Greenpeace's estimate, for instance, and both were done using satellite data (Oneill 2024). The case of the French researcher David Gaveau is also well known, as he was deported in 2020 for publishing forest fire data that contradicted official estimates (Rochmyaningsih 2020). This has also reflected in single cases, as the employment of EO in proceedings has been initially hindered; thanks to the awareness-raising of NGOs and expert witnesses the situation has however significantly changed, and police forces and national institutions generally favour the employment of EO in these cases (Saharjo 2023).

Companies have tried to stop the use of satellite data via a number of civil lawsuits against expert witnesses, where they accused them of lacking the expertise, and the tools the required accuracy to identify the damage. Lawsuits have demanded often remarkable compensations; the currently active case against Bambang Hero Saharjo and Basuki Wasis, brought by the company PT Kalimantan Lestari Mandiri, demands circa 16 million euros from the two forensic experts (Jong 2025). At the time of writing however all cases have been either been dismissed or ruled in favour of the experts.

3.4 REPLICABILITY

The methodology behind this application has been replicated in hundreds of cases (Prof. Saharjo alone testified in more than 800 forestry and mining cases). The application uses free, easily available data (such as those from the Sentinels), which can also be applied to similar cases in other regions. While this has proven very effective in Indonesia, it will however likely require some adaptations if it is to be used in sectors other than wildfires triggered by palm oil plantations or in other countries. Indeed, the use is very specific to criminal methodologies used in these cases (for instance in relation to preparatory actions, or the way fires are started), and it is very effective considering the Indonesian landscape (where plantations are particularly large and on largely flat terrain). The use of such an application on smaller fires (such as those taking place in Europe) or for different kinds of landscape or cultivation (soy production, the Amazon or Sub-Saharan Africa) could require some adaptation.

4. Remote sensing–based enforcement of environmental policies in Flanders

Entity responsible for the analysis: VITO-Remote Sensing (independent research centre)
Enforcement actor: Agentschap voor Natuur en Bos (ANB) (regional authority for environmental management)
Topic: Landscape change, deforestation, agriculture
Status: Consistently applied on the territory by enforcement agencies, actively used in enforcement
Main sources of satellite data: Sentinel-1, Sentinel-2
Replicability: Medium

All the information that is not otherwise cited has been provided by a representative of Vito and a representative of ANB.

4.1 OVERVIEW

The Agentschap voor Natuur en Bos (ANB), the agency charged with managing forests and nature in Flanders, and the independent company VITO, specialised in technological innovation, have partnered to develop a system able to recognise even minimal changes across the whole landscape of the region. The application compares a baseline obtained through regular scanning of the territory, monthly for grasslands and yearly for forests and small landscape elements, to satellite data obtained monthly in order to detect potentially illegal changes to the landscape. VITO has been responsible for developing the system and is now in charge of the analysis (concerning both the yearly updates of the baseline and the monthly monitoring); the ANB is instead responsible to perform checks on the ground in the cases highlighted by the application, and to impose remedial measures to repair public damage; if those are not carried out in time, they enforce a penalty payment. At the same time a criminal case file of the offense is compiled.

The application is structured around three main steps: production of a reference map, detection of changes and action on the ground.

The reference map has been realised based largely on the DHMV II datasets, provided by Digital Vlaanderen, the Flanders agency for the digital transition. This consists of full waveform LiDAR at 16 points/m^2 + 10cm RGB images, obtained from 2013 and 2015, and then updated through area-wide photogrammetric airborne images captured yearly. This will be updated in the near future, as Digital Vlaanderen will conduct a new series of LiDAR missions in 2026 and 2027 to develop the DHMV III datasets. Sentinel-1 and Sentinel-2 data are also used to complete the model. This reference map represents the baseline to which satellite data are compared on a monthly basis.

Detection of changes employs instead a mix of Sentinel-1 and Sentinel-2 data obtained through the Copernicus Data Space Ecosystem (CDSE) to obtain a cloud-free representation of the Flanders territory with a spatial resolution of 10 meters and a temporal resolution of five days. This representation is then compared to the baseline, to detect changes in the landscape and to highlight potentially illegal activities; while the first detection is done automatically by the system, locations flagged by the algorithm are then checked visually by VITO staff before being sent to ANB. The agency then sends an environmental inspector on

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Two images of the Flandres landscape employed in the case: a neutral one (first image), and one highlighting landscape elements and farms. Credit: VITO.

the ground to perform checks and eventually fine perpetrators. In 2022, for cases regarding sparse vegetation, the application automatically checked circa 60,000 polygons, flagged 2205, out of which VITO operators sent 157 cases to ANB. The agency performed 136 checks and issued 17 fines, however encountering only 19 false positives in the selection done by VITO.

This application has been applied so far only for the protection of historic permanent grasslands (HPG), one of the most relevant and protected kinds of landscape in the region because of its contribution to biodiversity, ecosystem services, carbon storage, water regulation and agricultural resilience, as well as its cultural and landscape heritage (Decreet Natuurbehoud 1997, Omzendbrief LNW/98/01). In this sense, the application allows to detect both major changes, such as the deviation of channels, and minor ones, such as the cutting of a monumental tree. From 2027, the application will be however extended to the protection of all small landscape elements (SLE) – such as ponds, stone walls, hedgerows and shrubs – and forests, because of the success of the instrument and the strong ecological relevance of such components of the landscape.

4.2 BENEFITS

The application presents significant savings in terms of time and resources thanks to its remarkable success rate (more than 90 per cent), and the automatisation of the system. As in Flanders farmers have to declare the expected use for their parcel for the upcoming year, the number of checks needing to be done was significant. A complete review of the territory was impossible as inspections were all done manually and, according to the ANB, some were done months or even years after receiving reports of potential violations. The implementation of this application thus not only reduced the need for

staff to perform checks on the ground, but also allowed for a full scan of the landscape that would have been otherwise impossible. In addition, the nature of this application allows for the detection of a variety of different environmental crimes, such as illegal logging, illegal water extraction and illegal waste disposal.

According to ANB and Vito, the high success rate and the completeness of the analysis has also had a significant deterrence effect on farmers; after implementation of this system, the number of fines has indeed significantly and steadily dropped. According to the two agencies, this has also been obtained through a good communication campaign, and positive press coverage of the initiative.

4.3 OBSTACLES AND LIMITATIONS

Obstacles and limitations to this applications are limited, and they mostly relate to its replicability (see "Replicability" section of this case).

The major obstacle faced by VITO during the development of the system was to guarantee a high success rate. Otherwise, an excessive number of false positives could have undermined trust in the application on the part of nature inspectors, and ultimately lead to its abandonment. In this sense, visual analysis by VITO staff in the report still plays a relevant role to guarantee its success (reducing however the automatisation of the process). Scripts to perform the automatic analysis were also run manually until March 2025, further increasing the role of active staff in the system; this has however changed, as it has been automated through an API.

The system also relies on a detailed baseline (the DHMV II dataset) that needs to be updated (as the system already does yearly) and, at some point in its existence, revised. Considering the expected update for the DHMV dataset in 2026–

2027, this however will not likely be an issue for the next decade, and the revision should happen with no major costs for the agencies involved.

A last obstacle that will remain consistent is supervision by nature inspectors. The supervision is required since the chemical alteration of the vegetation is not always detectable from satellites and needs to be done through in-person monitoring.

4.4 REPLICABILITY

Although the maturity and success of this application could allow for significant replicability, it is also a particularly location-specific system that would require a few conditions to be met in order to be reproduced. Its success indeed depends also on key elements such as the existence of a detailed baseline (the DHMV II dataset) and a small territory with specific features (Flanders is mostly flat and largely homogeneous), which may not be available in other countries. The system also builds on landscape elements that are specific to the region and that are rather well analysed by EO methodologies – SLE are indeed a key element featured in the Copernicus Land Monitoring Service, for instance[77]. Expanding to other landscape elements, especially if less researched, could be then complicated or expensive. Generally speaking, the need for a high success rate (in order to push agencies toward using the service) and for the detection of small changes require a significant adaption of the system to be employed on other kinds of landscape, and in other countries or regions.

77. Copernicus Website: High Resolution Layer Small Landscape Features.

5. Illegal mining investigation in Bangka Belitung

Entity responsible for the analysis: Prof. Bambang Hero Saharjo, IPB University (academia)	
Enforcement actor: Deputy Attorney General for Special Crimes	
Topic: Illegal mining	
Status: Used in active and concluded cases, used as evidence in court	
Main sources of satellite data: Sentinel-1, Sentinel-2	
Replicability: Medium to high	

All the information that is not otherwise cited has been provided by Prof. Bambang Hero Saharjo.

5.1 OVERVIEW

In 2024, the Indonesian attorney general's office uncovered one of the largest corruption cases in the country in recent times, concerning illegal tin mining in the Bangka Belitung islands (Jong 2024). The case has received significant attention nationally and internationally, and has seen a significant contribution of EO, particularly in detecting the illegal mines and in estimating the economic and environmental damage.

Illegal tin mining has been an issue in the islands for decades, but the problem spiked in recent years as demand for the critical mineral rose, also because of the energy and digital transition, and legal reserves started to decrease and extraction costs to increase. Illegal mining grew from the early 2010s and then from 2018 as PT Timah, the public company running the legal mines, increased its sourcing of tin from illegal inputs to maintain a steady level of exports (The Gecko Project 2025). The area is indeed crucial not only for Indonesia, but for the global supply of tin – circa one fifth of all tin comes from Bangka and Belitung (The Gecko Project 2025). As illegal mining soared, PT Timah's own activities expanded beyond authorised areas, over circa 170,363 hectares (more than double the concession area) (Jong, 2024). Due to the proliferation of small-scale illegal mines, the total extraction area is however much higher, as in 2024 it was estimated it covered approximately half of the surface of the islands (BBC Indonesia 2025). Legal and illegal activities are also conducted offshore through excavation of the sea bed (in most cases using artisanal methods) (The Gecko Project 2025).

Illegal mining in the islands has had a massive impact on the environment, the health of communities and their income, and has resulted in tax losses estimated at circa 15 billion euros (Wijaya 2024). Wildlife habitats, natural parks and areas highly valuable for biodiversity have been subject to excavation activities. Pollution from offshore extraction and from mine tailings have impacted fishing, with the income of local fishermen being halved in some of the most affected areas (Arnanda et al. 2021). Soil contamination and disruptions to the water cycle also impact wildlife and native vegetation, further exacerbating the damage to ecosystems, and even triggering a wave of crocodile attacks as they

Areas in Indonesia where deforestation occurred for illegal mining activities, before (first image) and after excavations (second). Credit: Bambang Saharjo.

were pushed towards human settlements by mining activities (Adrian Fajriansyah 2024).

EO played a crucial role in understanding the extent and criminal methodologies behind the illegal mining, also because most activities have been hidden for years through extensive corruption of local enforcement officers, local authorities and representatives of PT Timah. Indonesia's Attorney General's Office commissioned the analysis to Prof. Bambang Hero Saharjo, expert witness for Deputy Attorney General for Special Crimes, in order to understand the extent of activities and damages.

Prof. Saharjo used manual scanning of optical, medium and high resolution satellite imagery of the islands to identify all mined areas. Data from Sentinel-2 and Landsat 8/9 covering the years 2015–2023 were used; objects in tin mining areas were identified through an image classification process to discover and differentiate elements related to mining activities. This identification used a visual interpretation method that relied on factors such as colour, shape, size, texture, patterns, shadows and spatial relationships between objects. The interpretation process provided a variety of information about land use, including the actual location of tin mines and other connected infrastructures, as well as other landscape elements indicating extraction activities – usually tin mining areas can be identified by the presence of ponds and river flow patterns. The study followed several different stages, including image pre-processing, visual interpretation of the images, creation of class identifiers for image classification, ground checks or sampling plots from Google Earth Pro and accuracy testing. The overall accuracy of the detection widely exceeded a threshold of 85 per cent; the value was chosen as it is established by the United States Geological Survey (USGS) as the minimum acceptable threshold for classification and interpretation of remote sensing data (Tyukavina 2025).

5.2 BENEFITS

The application has been crucial to understanding the impact of illegal mining in the area, and a central component of the still-ongoing investigation of the case. Indeed, all estimates of environmental and economic damage (including those cited in this report) have been obtained through Prof. Saharjo's EO analysis.

Traditional methodologies would scarcely have obtained such a result, for a number of reasons. Most of the territory in Bangka Belitung is hard to access, and corruption and the role of influential individuals on the islands make inspections even more complicated. The extent and pervasiveness of illegal mining in the territory would have also made a complete evaluation of extraction activities particularly long and complicated if done only through missions on the ground, and the results would have hardly reached the level of accuracy obtained by EO.

Satellite data also offered the possibility to easily compare the detected extraction activities against the borders of concessions, natural parks, forest areas and other such GIS information. In particular, the application adopted the Topographic Map of Indonesia (RBI) at a scale of 1:250,000, the Map of Indonesian Forest Areas, the Land Cover Map 250K, the Regional Administrative Boundary Data and the Mining Exploration Permit (IUP) for Bangka Belitung. This allowed for a significantly easier detection of offenses such as the expansion of mining activities beyond concession areas by PT Timah, illegal mining in national parks and conservation areas, and mining in forest areas without permits. Offenses also involved different stages of the supply chain, as EO also helped detect smelters operating in violation of regulations, with significant environmental damage in surrounding areas. Satellite imagery also showed that most operational activities in the field neglect safety during mining exploration. It indeed indicated

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that only a small percentage of such activities utilise standard field operational facilities and infrastructure, as most utilise rudimentary infrastructure, including personal equipment. Notably, the use of EO also allowed for the detection of another major environmental offense, the almost complete lack of restoration and reclamation activities post-mining, and of rehabilitation of water bodies – all compulsory under Indonesian law. Abandoned mines appeared to be heavily contaminated and in some cases particularly large – even reaching 200 hectares.

Finally, EO allowed for the evaluation of illegal activities and environmental damages over time (from 2016). As investigations started only in 2022, without EO inspections on the ground would have only recorded a "static" image of the situation. By comparing images from different years, this application instead made it possible to uncover the dynamics of the expansion of illegal mining, to understand which areas were affected before others, to detect complementary activities (such as the opening of roads) and to discover when and how certain locations were abandoned. This in turn is helping investigate the interactions between PT Timah and illegal miners, uncover the culprits, as well as fully understand the environmental impact over time.

5.3 OBSTACLES AND LIMITATIONS

Obstacles encountered by this application concern some technical limitations faced by optical imagery, but are largely concentrated around issues generally related to the investigation.

Indeed, tin mines are open-pit, employing water with chemical components that enhance its colour and make detection relatively easy even without VHR satellite imagery. The areas affected by excavations also generally large. Like most tropical countries, Indonesia however suffers from a consistent cloud cover, that is a frequent obstacle in the employment of optical satellite imagery. As this case considers a long span of time and has generally no need to find data for specific dates, this was however not a major obstacle for this application. Prof. Saharjo also employed mosaic images produced quarterly by the Copernicus programme using Sentinel data, which are cloudless and could be employed to scan the territory for changes to the landscape (such as the opening of new mines).

The major obstacle likely faced by this investigation was instead the backlash faced by Prof. Saharjo following the conclusion of its evaluation and the sentencing of six people in January 2025. National media published strong criticisms against the professor, accusing his work of being largely inaccurate, and going as far as declaring that ecological losses could not be used as evidence in a corruption case[78]. Lawyer Andi Kusuma even filed a police report against Prof. Saharjo, stating that he represented the people of the islands, and that the professor "put the tin mining industry in a bad light" (Jong 2025). The accusations were strong although unjustified, as the judge had already accepted the report as admissible evidence during the trial. Despite even a coordinated campaign on social media to attack Professor Saharjo, public support was strong and the accusations quickly disappeared. At the time of writing, there are no lawsuits pending against him; the instrument of Strategic Lawsuit Against Public Participation (SLAPP) is however common in Indonesia and has been frequently used to discourage public action against environmental cases (also against Prof. Saharjo himself, see **Case 3**).

While the EO application has been successful, addressing illegal tin mining in Bangka Belitung

78. Environmental Defender website: Bambang Hero Saharjo.
79. *Ibid.*

remains complicated. The first six defendants were sentenced in December 2024; despite the prominent role of the offenders (CEOs and directors of companies operating as part of PT Timah) and the strong environmental impact of the case, sentences have been however lenient[79]. Illegal mining in the islands also appears to continue, although at a reduced scale (Jong 2024).

5.4 REPLICABILITY

The methodology behind this application is considered to be easily replicable, since it is the pattern consistently used by Prof. Saharjo and other expert witness in Indonesia to handle natural resource-related cases. It has been employed also for illegal coal mining, for illegal oil palm plantations and for illegal mining activities in forest areas. The application uses free, easily available data (such as those from the Sentinels), and a detection system based on patterns that are common across such cases also in other regions and in other sectors (illegal coal mining and illegal coal storage in South Africa, and illegal rare earth mining in Myanmar, for instance). It is however worth noting that replicability concerns cases that share some of the key features of this one: a large time scale to be considered, medium to large mining areas to be detected, and highly visible open-pit mining. This application would likely require significant adaptation to uncover activities on a lesser scale or performed under the forest canopy (as in the Amazon, see **Case 10**) or that would need detection at specific times.

6. EO to detect and intercept fishery crime by the European Fisheries Control Agency

Entity responsible for the analysis: European Fisheries Control Agency (EFCA) (European agencies)	
Enforcement actor: Member States Fisheries Control Authorities & 3rd country stakeholders	
Topic: Illegal Unreported and Unregulated Fisheries (IIU)	
Status: Implemented for monitoring and enforcement cases	
Main sources of satellite data: Sentinel-1, Sentinel-2, Copernicus Contributing Missions	
Replicability: High	

All the information that is not cited have been provided by a representative of EFCA.

6.1 OVERVIEW

One of the organizations that uses EO extensively and methodically to perform fisheries surveillance globally is the European Fisheries Control Agency (EFCA). EFCA is responsible for promoting and organising the coordination and cooperation between national fisheries control and inspection authorities so that the rules of the Common Fisheries Policy (CFP) are respected and applied effectively.

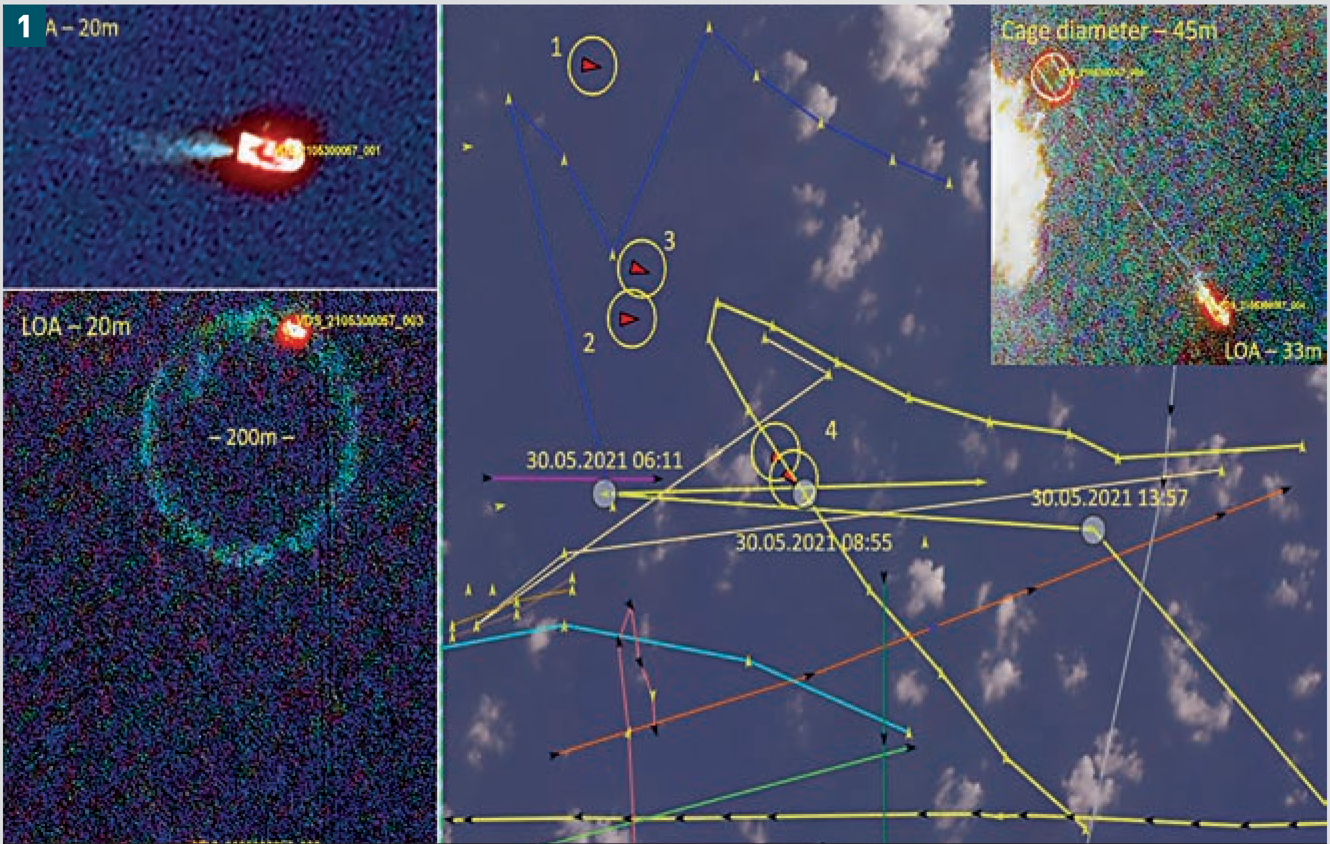
The area of operation is vast, as it covers not only the European Union waters, but also European countries' exclusive economic zones (EEZ's) and International Waters[80] (i.e., North Atlantic, West Africa, Indian Ocean), which make up about 80% of EFCA-monitored waters.

EFCA has longstanding cooperation with the European Maritime Safety Agency (EMSA), SATCEN and cooperates with ESA under a specific MoU. This allows EFCA to have access to a complete and integrated maritime picture through wide area surveillance using SAR imagery, vessel detection using correlation algorithms for the identification of potential inspection targets, and provision of high-resolution SAR and optical imagery on request, available through the Copernicus Contributing Missions (EMSA, 2018). The majority of the images used are SAR with 20 to 2m resolution; about 85% of the images have these characteristics, while during specific requests, high resolution SAR (0.5m resolution) is available.

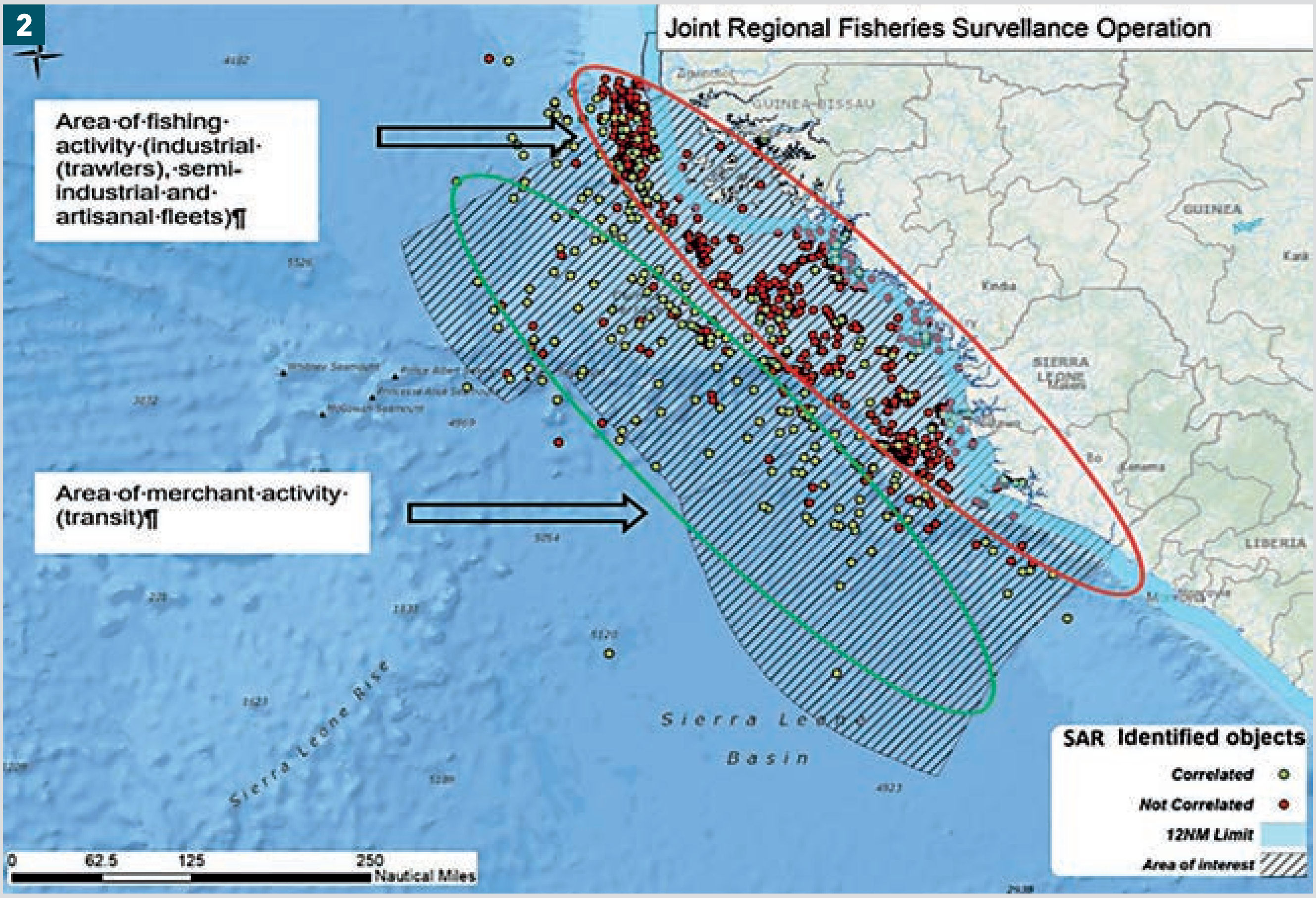
Outputs of the said services are used and integrated at EFCA with other data sources, such as vessel position data and other relevant fisheries-related information, in a 'toolbox' approach. This feeds into either a risk analysis approach or is used for direct operational and tactical support for fisheries control operations. With this objective in mind, a Space & Surveillance Technologies Support Hub was created at EFCA which provides for enhanced tools to transform EO data intointo actionable deliverables to support its own operations and those of EU Member States fisheries control authorities. EO vessel detection outputs are automatically correlated with Vessel Monitoring Systems (VMS), which track licensed fishing vessels via mandatory onboard transponders, and Automatic Identification Systems (AIS), a broader maritime tracking system used by many commercial vessels. The resulting outputs are used for EFCA's own operations, the National European fisheries, control authorities and the European Commission; the analysis is not open access for the wider public.

There are two main services that EFCA offers: routine monitoring and rush mode or short notice, which is specifically requested by member states in a precise maritime zone. A typical example of the routine mode can be seen from the operation in Bassas da India in the Indian Ocean.
In the Indian Ocean, the French EEZ encompasses numerous islands and atolls, which host an enormous wealth of biodiversity and serve as a nursery area for marine life. Consequently, many of these areas are declared Marine Protected Areas (MPA). Its remoteness and size pose a particular challenge when it comes to ensuring the continuous presence of patrol assets in the area. In June 2022, routine CMS acquisitions topped up with high-resolution optical imagery were ordered and analysed in support of French patrol units in the area coordinated by the French Fisheries Monitoring Centre. The analysis detected small vessels within the Zélée Bank MPA. Consequently, a French fisheries patrol vessel was dispatched to the area for further investigation. Upon arrival, about 20 km eastwards of the initial position, the inspection team was able to intercept a fishing vessel with eight crew on board, and 126 kg of illegally caught fish, 14 fishing lines, and 11 harpoons were apprehended (EMSA, 2022). Although this case focuses on small artisanal fishing vessels (around 10 m in length), their impact can be devastating for the fragile ecosystem.

A subsequent example of the work of EFCA has been in the Mediterranean, within their regular monitoring activities. Following the acquisition of various SAR images, a cluster of small fishing vessels was detected in an area known to be prone to use of driftnet (a fishing practice which is illegal). Using a tip and cue approach, a series of high-resolution optical imagery was ordered in an attempt to detect potentially illegal fishing



Two images from EFCA's analyses of detected vessels in areas of fishing and potentially illegal fishing activities. Credit: EFCA



activity. Systematic analysis and processing of the optical imagery indeed revealed the presence of such driftnets, as the floating devices could be visualised, and even allowed for measuring the length of the deployed gears. Follow-up operational deployment in the area led to the interception of one of the vessels involved in this illicit activity.

6.2 BENEFITS

For almost a decade now EFCA is rolling out and developing the use of EO for fisheries surveillance, in close cooperation with the relevant entrusted entities and space technology bodies. Since then several advantages have come to light.

The first is cost efficiency: due to their remoteness and extent, patrolling the high seas with classic means is quasi-impossible or comes at a very high cost. Focused operational outputs can provide 24/7 guidance to surface and air maritime patrol means, thus ensuring cost-effective and targeted deployment of patrol means. This has a major impact on fuel and other operational costs.

The reliability of the operations is equally relevant. EO technologies are mainly used to support operational activities, which ultimately could result in legal proceedings; any deliverable produced needs to be complete, trustworthy, and authenticated. Furthermore, the data and information sources and methodologies used need to be classified and verified in terms of reliability. Performing continuous quality and reliability checks, EFCA ensures that the outputs are the best possible base for launching operational actions or legal proceedings.

Thirdly, the effectiveness of the operations, the EO images provide a real and measurable impact on the capacity to detect non-compliance. The images are used to constantly monitor the maritime areas, and additional short-notice requests can track the exact and current position of the vessels and indicate it to the closest EU vessel for interception, as in the case of Bassas de India.

Lastly, as most of the EO use to monitor environmental crimes, deterrence is a strong value added. When vessels conducting illegal activities know that they are constantly monitored and intercepted, the number of illicit diminish, since the knowledge of being under constant surveillance discourages potential criminals. EO imagery effectively increases the window for AIS and VMS monitoring. When a vessel is detected, its position is cross-referenced with these tracking systems. This allows for the identification of 'dark vessels', those operating with transmitters disabled to mask potentially illegal activities.

6.3 OBSTACLES AND LIMITATIONS

There are still certain obstacles and limitations related to the technological and structural levels, which can be summarised in coverage and time, flexibility, and structural issues with third-country partners.

In terms of coverage and time, despite the vast reach of Sentinels, and contributing missions, important gaps revisit time remains, meaning that the vessels can appear and disappear between acquisitions. Additionally, VHR SAR images are needed to detect small artisanal vessels, as was the case for Bassas da India, which have a smaller coverage and are often very costly. The tip and cue approach, while effective, adds processing time, and ordering high-resolution optical imagery after an initial SAR detection introduces delays that can reduce the probability of successful interception. As per short-notice requests, while available, they depend on satellite tasking schedules and cannot always be fulfilled immediately, limiting the responsiveness of the system in time-critical situations. Finally, one of the largest obstacles is that EO technologies are still not fully adapted for the maritime environment, and still most of the R&D is focused on land mass monitoring. Therefore, there is still limited usability of what could instead be achieved.

Flexibility also has some gaps related to the constant coordination between EFCA and the entrusted providers. The dual-mode system requires constant synchronisation between EFCA officers, member state authorities, and patrol assets, creating organisational complexity that can slow down operational responses. The issue of visual confirmation, depending on the weather and cloud coverage, is also persistent, as in the Mediterranean case, to visualize the driftnets, optical VHR images, the weather conditions needed to be optimal.

Lastly, structural issues with third countries, as is the case with West Africa, prevent the spreading of the know-how. To promote the fight against IIU fishing, EFCA is contracting party to various projects with third countries, funded by the European Commision, to create training, operational coordination, and capacity building. These programmes are an important part of EFCA work, and they support the development of a sustainable and inclusive blue economy and the preservation of marine resources. The limitations here are related to the coordination and the lack of resources in third countries. In West Africa, EFCA is involved in the West Africa Sustainable Ocean Programme (WASOP) to combat IUU fishing[81]. Here, there are several issues and obstacles related to the enforcement, while EFCA signals the potential illegal vessels, West African countries often lack the resources and operational capacity to use the information provided. Additionally, governance challenge and governance challenges in some partner countries mean that actionable intelligence generated by EFCA does not always translate into enforcement action on the ground, undermining the deterrence value of the monitoring system.

6.4 REPLICABILITY

The replicability of the system is strong; it is already operating at a global scale, covering not only European waters but also International Waters across the oceans.

The request for support from EFCA is straightforward and can be used by either Member States or the European Commission. The toolbox integration model, combining EO with AIS, VMS, and HUMINT, is modular and adaptable, meaning individual components can be adopted by agencies that do not yet have access to the full suite of data sources.

A key constraint on the system's effectiveness is the limited financial and human resources available to EFCA. Given the ever-increasing request for support, assigning adequate resources is often challenging, in particular considering the worldwide monitoring needs and thus the need for a 24/7 support. Nonetheless, this system is well-suited for replication by other Regional Fisheries organisations operating in the Pacific, Indian, and Atlantic oceans, where existing mandates and member state structures already provide a foundation for institutional adoption. Integrating EO monitoring into these frameworks would therefore be relatively straightforward.

80. International waters are surveilled in the framework of EU commitments vis-a-vis Regional Fisheries Management Organisations (RFMO's). In addition, EFCA supports the coordination of a number of international projects which include the need to monitor the territorial waters and EEZ's of a significant number of Coastal States in West Africa and the Indian Ocean region.

81. Expertise France website: WASOP - West Africa Sustainable Ocean Programme.

7. Detection of illegal mining in India: Mining Surveillance System (MSS)

Entity responsible for the analysis: Bhaskaracharya Institute for Space Applications and Geo-informatics (BISAG-N) (national research institute)
Enforcement actor: Indian Bureau of Mines (IBM), State Department of Mines & Geology (DMG), State Mining Secretary (environmental ministries and agencies)
Topic: Illegal mining
Status: Currently applied for surveillance and enforcement
Main sources of satellite data: Landsat-8, Landsat-9
Replicability: Medium

All the information that is not otherwise cited has been provided by a representative of BISAG-N.

7.1 OVERVIEW

The Mining Surveillance System (MSS) is a satellite-based programme for monitoring mining leases in India. The MSS has been developed by the Bhaskaracharya Institute for Space Applications and Geo-informatics (BISAG-N) and Indian Bureau of Mines (IBM) to identify illegal mining across the country. BISAG-N is the State Agency for GeoSpatial Information Systems of the Government of Gujaratan, however participation in the programme has been expanded to other Indian states. The MSS has been operational since 2016. It combines optical data obtained through EO with authenticated registration maps of mining lease areas, to identify activities carried out outside of these parcels allocated for mining. The dataset used is obtained through the Landsat programme, but the system is compatible with any dataset offering moderate 30-meter spatial resolution, which includes Sentinel-2 (which provides high-resolution optical imagery at 10m, 20m and 60m for land monitoring). Registration information and boundaries of mining leases are provided by the IBM. The optical data are then scanned and compared to the leases by BISAG-N officials. Any unusual land use change observed on satellite imagery in a zone up to 500m outside the boundary of any authorised mining lease area is flagged as a trigger in real time to the state government to check for illegal mining. The units dispatched for such control depend on the state in which the site is located. Responsible authorities include the State Department of Mines & Geology (DMG), State Mining Secretary, State Office and Headquarters Office of IBM and Ministry of Mines. The infringements are divided into two categories (major or minor minerals) depending on the nature of the mining sites[82]. During the first and second phases, from 2016 to 2021, 950 triggers were generated by the MSS. During the third (2021–2022) and fourth phases (2023–2024), a total of 472 alerts were generated. State governments acted on just 51 per cent of these alerts and 14 per cent resulted in the actual detection of illegal mining.

7.2 BENEFITS

The main benefit of the system is the monitoring of a large set of highly fragmented mining lease areas. The Indian mining sector is composed of both large-scale mining sites – usually copper and iron ore – and smaller ones, whose boundaries tend not to be easily apparent when surveillance is conducted by units on the ground. The MSS offers both a large-scale spatial perspective and the possibility to refer to the boundaries of the allocated mining parcels. The fact that triggers are automatically enacted by officials upon detection is also another benefit, accelerating possible inspections by the receiving officials. Another advantage is that end-user utilisation of the MSS requires little expertise and training on the part of enforcement officers; a mobile app has been developed and state governments are able to access the application with the user ID and password provided to them for the purpose of verification. This makes utilisation of the system possible even with limited technical expertise and without the creation of special technical departments within the enforcement authorities. Furthermore, training for officers has also been organised by BISAG-N and IBM to further facilitate the adoption of MSS, especially in mineral-rich states.

7.3 OBSTACLES AND LIMITATIONS

The main obstacles and limitations of the MSS remain its difficulties in distinguishing real unauthorised mining actions from other non-illegal actions conducted at the boundaries of concessions. This is specifically common for mining leases of minor minerals sites, whose average extension in India is quite limited in terms of hectares. Furthermore, these sites are sometimes intermixed with areas dedicated to other economic, agricultural or other activities. Therefore, this increases the possibility of false positives when inspecting smaller sites, with actions identified as mining activities adjacent to mining leases actually turning out to be normal activities in these areas. Additionally, it is difficult for the system to detect illegal activities inside the boundaries of a legal mining site, such as overquota extraction of specific materials. Specifically, the MSS cannot detect violations that do not affect surface soil, such as “rat-hole mining”, an

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Images from two areas at risk of illegal mining and subject to the monitoring: Jharia Coalfield Belt (first image) and Jaintia Hills District (second). Contains modified Copernicus Sentinel data (2026), processed by ESA.

underground mining activity banned by National Green Tribunal but still widespread in Meghalaya, in which narrow vertical tunnels are dug to reach thin coal seams. Another major limitation of the programme is that while triggers are quite rapid, the capacity of the state authority to translate alerts into action can be quite slow and inspections can take years to conduct after alerts have been received. Another limitation, given the Indian lease system, is the difficulty of comparing leases of minor minerals – such as sand and stone – which are not collected in a single repository, unlike major minerals.

7.4 REPLICABILITY

The MSS is considered replicable due to both the limited technical expertise needed and the limited degree of adaptation required to extend its application to new geographical contexts. The system has already shown its replicability by progressively being extended to additional Indian states with minimal changes to its framework. Regarding replication in other jurisdictions, the primary requirement for extending an MSS-model programme lies in two factors: ensuring access to moderate-to-high-resolution images and the presence of an extensive and regularly updated system of mine registration. Obtaining the kind of images needed is easier, thanks to the endowment of free data from the Copernicus programme and Landsat; however, the lack of an efficient, standardised and centralised framework for mine registration, especially in jurisdictions with large and heterogeneous geological areas, may hamper the replicability of the MSS.

An MSS-model programme may also be applied to recognise different categories of other landscape-transforming illegal activities as well, such as illegal deforestation. This could be accomplished by using the same category of optical satellite data and comparing it with regis-

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tries of protected forested areas – similarly to illegal mining, monitoring personnel noticing discrepancies between clearings operations and areas in which such actions would be illegal could notify the responsible officers for inspections. This expansion of scope, however, would also require an increase of coordination between the Ministry of Mines and the Ministry of Environment, Forest and Climate Change (or similar authorities in other countries).

82. Minerals are categorised as major or minor depending on Section I (a) of the Mines & Minerals (Regulation & Development) Act, 1957. Major minerals include, among others, copper ore, iron ore, gold, tungsten concentrates, tin concentrates and zinc concentrates. Minor minerals include, among others, granite, gravel and lime shell.

8. Reducing human-wildlife conflict and poaching in Sub-Saharan Africa

Entity responsible for the analysis: EOLAS Insight (private consultancy company)

Enforcement actor: national parks authorities in Mozambique via the Peace Parks Foundation

Topic: wildlife crime

Status: applied on monitoring, still to be scaled up and used in mainstream applications

Main sources of satellite data: Sentinel-2, Sentinel-3, private providers

Replicability: High

All the information that is not cited have been provided by a representative of EOLAS Insight.

8.1 OVERVIEW

The private consultancy company EOLAS Insight has developed a system involving the combination of EO with other data, to estimate risk factors and risky areas for human-wildlife conflict (HWC) and poaching. The aim is to share this information via easily navigable maps to park authorities, to locate the areas where wildlife crime may occur, and improve its prevention.

The two offenses are indeed closely linked: poaching is not only triggered by the demand for wildlife products (such as ivory for elephants), but also by the destruction of ecosystems, which in turn reduces buffer zones between human activities and natural habitats, increases the impact of endangered species on farming and herding, and thus pushes local communities towards conflict and killing to prevent damages.

This application aims at preventing HWC and poaching by understanding factors influencing conflict, specifically of two kinds: human factors, i.e. the impact and extent of location of human activities over the territory (farming, herding, building of settlements, for example), and animal factors (e.g. seeking food and water during the dry season). In this sense, the application's objective is to understand landscape, weather, climate, and ethology elements to try and foresee the animal's behaviour and movements and identify potential HWC and poaching hotspots.

This application thus creates a risk layer of areas where HWC may occur by combining different kinds of data: Sentinel-2 and Sentinel-3 optical and multispectral imagery (and more specifically ESA's WorldCover)[83] represent the backbone of the information, providing data about vegetation cover and its seasonal changes, land use and land use change, existence of human settlements, among the others. The layer also integrates the borders of natural parks and other protected areas, buffer zones between these and developed zones, ecological corridors. It also uses information about animals movements and behaviour from tracking collars, such as migration routes, and about human activities, such as herding and cultivation.

All these data are then combined to produce a strategic overview that highlights potential hotspot areas where human activity and elephant populations may come into contact and, therefore, where wildlife crime is most likely to occur. The information is then transmitted by EOLAS to the Peace Parks Foundation, which in turn

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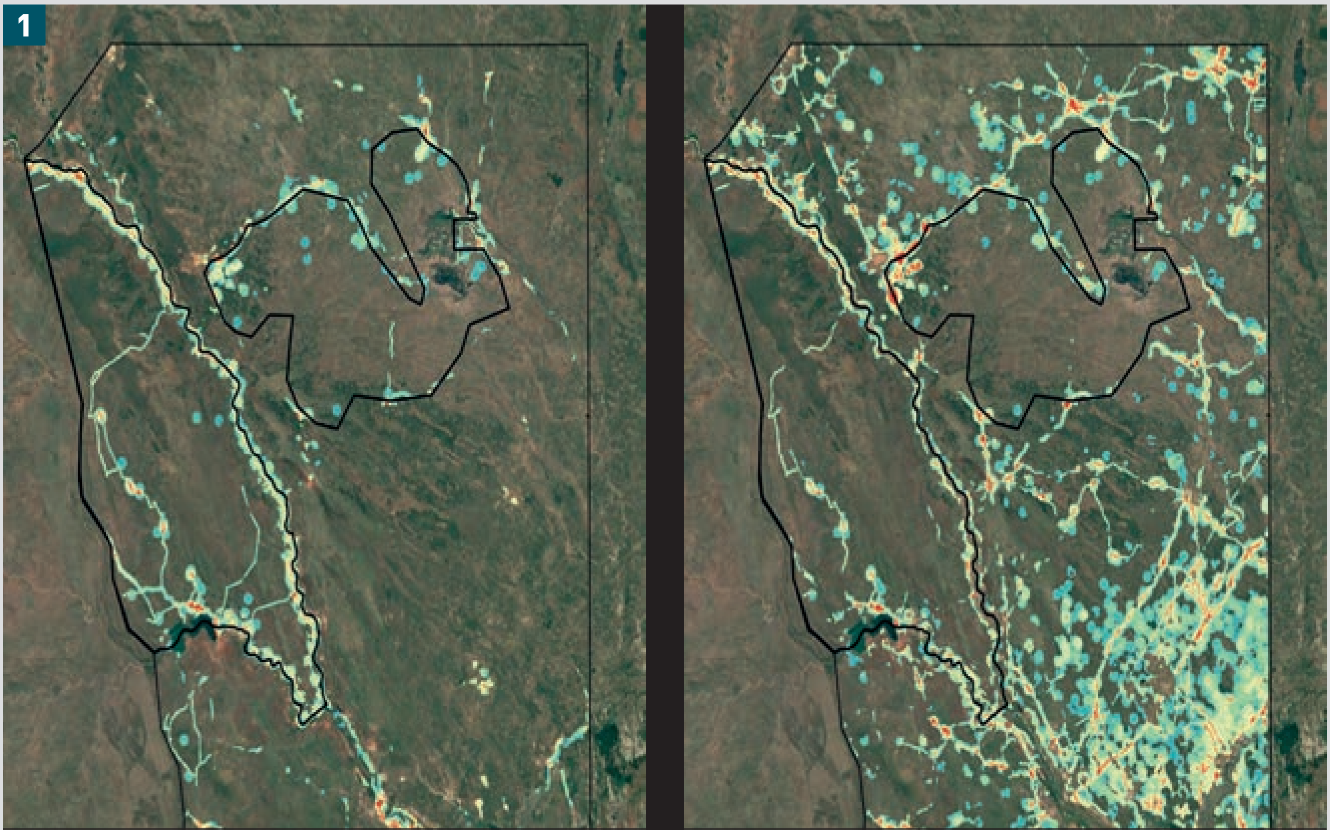

Two images highlighting the detection of settlements in potential areas of conflict (first image), and sightings of elephants in the same location (second image). Credit: Eolas.

shares it with different organisations operating in the area (Mozambican police, park authorities, etc.). The data have been used so far for planning ranger patrol routes and identification of potential poaching hotspots.

The methodology was originally developed for managing red-deer populations in Scotland, but it then scaled-up and applied to HWC in Sub Saharan Africa thanks to the ESA funded project *Mapping Wildlife Corridors for Effective Park Management in Africa* between 2024-2025. Currently, the application has largely focused on African elephants in Mozambique, with also a test in Mali.

8.2 BENEFITS

This application is one of the few that has a primary focus on pre-emptive action; it is a major advantage with regard to environmental crimes and wildlife crime in particular, since restoration actions for the sector are particularly complicated and in several cases impossible – this is particularly the situation for endangered or long-lived species, such as the African elephant.

This application has also a strong focus on integrating different sources of intelligence – OSINT, human intelligence, ecological considerations. As a consequence, the application not only empowers the use of EO, but also provides a multifaceted tool that can be used beyond wildlife crime: indeed, it can support rangers in a number of interventions, regarding livestock management, planning watering, resettlement of communities, as well as deciding where and if to fence land.

Compared to traditional methodologies, this can be used to better target the patrolling resource towards likely hotspot areas, and increases the accuracy of inspections compared to those done without EO analysis. Wildlife crime is often committed in sparsely populated areas, and in large territories which are frequently hard to access. Patrolling is thus often complicated and expensive, especially when criminal methodologies are changing, and applications that can reduce the range of work of rangers provide crucial benefits to enforcement.

8.3 OBSTACLES AND LIMITATIONS

Being a relevant yet relatively new application, there are still limitations to its implementation. A few elements are still complicated to detect, such as small cultivations or areas that are planted seasonally. The methodology is also facing complications in counting the animals or tracking their movements using EO – Sentinel or Landsat imagery does not have the required resolution, and VHR images do not have the required frequency for detection. Thus, they usually rely on animals with radio collars, and since collaring animals is a time-consuming and expensive activity this may hinder the effectiveness of the application. It is also particularly complicated to detect animals when going through particularly risky areas (such as ecological corridors), as they tend to spend only a little time there, and thus information are less available.

Accessing poaching data to validate and improve the AI modelling has also proved difficult as these data are held by law enforcement organisations who are concerned about releasing it. A secure data sharing infrastructure would support sharing of sensitive data and would also allow a more streamlined enforcement chain compared to the current one where data is passed to Peace Parks then onto local enforcement staff.

8.4 REPLICABILITY

The application has the potential to be replicated across different regions and in different

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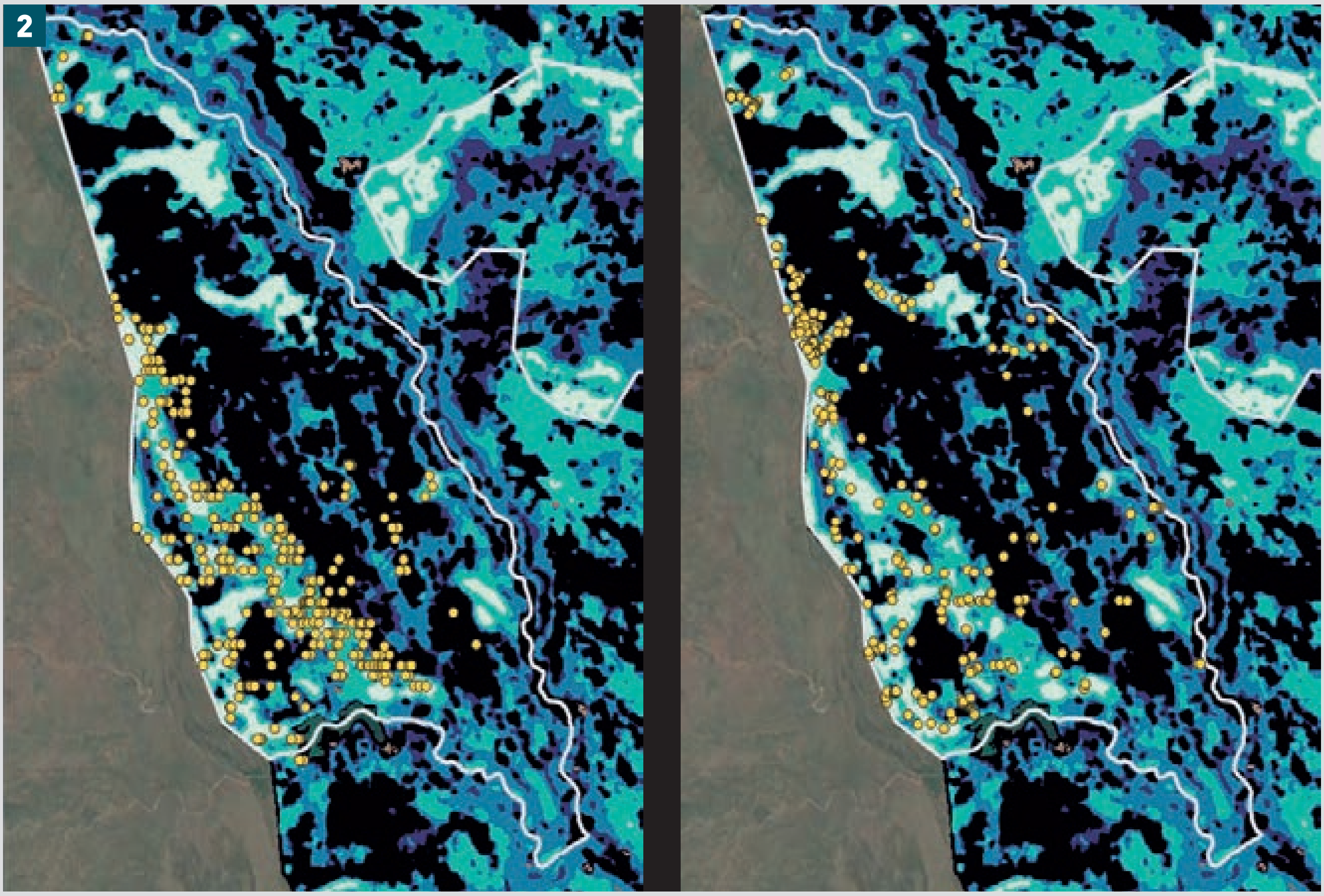

cases of HWC and poaching. The EOLAS team is evaluating using the system for elephants in other parts of Africa, as well as adapting the system to other species such as wolves, deer, and boar in Europe. The model is indeed flexible enough to be easily adapted to a different context; however, its replicability heavily relies on the availability of EO and particularly non-EO data for the region. If ecology, ethology, human behaviour and other information about the area are readily available replicating the model would require little additional effort, while a scarcely investigated zones would instead demand significant adaptation action.

83. See ESA website: land mapping.

9. AI detection of illegal landfills and solid waste in Northern Italy

Entity responsible for the analysis: Politecnico di Milano (Polimi) (academia)	
Enforcement actor: ARPA Lombardia (regional agency for environmental protection)	
Topic: Illegal waste disposal, waste trafficking	
Status: Applied in environmental monitoring and potentially in enforcement cases	
Main sources of satellite data: Copernicus Contributing Missions (WorldView 3 – Pléiades Neo)	
Replicability: High	

All the information that is not otherwise cited has been provided by a representative of Polimi.

9.1 OVERVIEW

The Politecnico di Milano (Polimi) has developed a system to automatically identify solid waste illegally disposed of in the Italian region of Lombardy, using very-high-resolution remote sensing (VHR RS) images, with a resolution higher than 50cm/px, and artificial intelligence (AI) developed by its researchers (Gibellini et al. 2025). The model is particularly relevant since, unlike most applications in the sector of waste detection, it has achieved a remarkable 94.56 per cent accuracy level. The system has been initially developed as part of the Perivallon project,[84] and has since been adopted by ARPA Lombardia, the regional agency for environmental protection in the Italian Lombardy region (which also includes the city of Milan and the core of Italian industry).

In the framework of this application, Polimi acquires VHR RS images from Copernicus Contributing Missions covering the territory of four municipalities in the Italian region, every three months. The providers are in most cases Airbus and Maxar. The AI then scans the images and detects possible locations of solid waste, providing a map of sites with a standardised colour coding highlighting the level of confidence. This map is then sent to ARPA, which will then proceed to perform checks on the ground in the most plausible locations for illegal waste disposal, and use the data gathered for investigations and/or the issuing of fines.

The satellite detection is also matched by an extensive adoption of unmanned aerial Vehicles (UAVs), which are used by ARPA to conduct operations in the field. The agency employs advanced commercial drones (DJI Matrice) to take detailed images, but also to develop a 3D reconstruction of the site and a georeferenced orthomosaic. The Polimi team has also developed AI for the recognition of the types of solid waste in the UAV images; it is able to distinguish between seven different kinds of waste material (such as "tires" or "textiles") (Morandini et al. 2025). This feature has proven particularly effective for the detection of asbestos.

9.2 BENEFITS

The application has a number of advantages, compared to both traditional monitoring and other satellite applications in the sector. Concerning the latter, this tool is indeed one of the few with a very high detection accuracy level, and able to detect even smaller waste disposal sites (such as those found on roadsides or in industrial or agricultural areas, which are frequent in the Lombardy landscape. Other EO tools indeed mostly focus on the monitoring of large waste facilities and major landfills (Morandini et al. 2025).

Compared to traditional, on-the-ground monitoring of the territory, both ARPA and Polimi indicate relevant savings in terms of overall coverage of the total area, and in the time employed for checks. Estimates from the two entities indicate that inspecting the territory of the four municipalities for illegal waste disposal takes circa 30 per cent time less than with traditional methods (Gibellini et al. 2025). Thanks to the application, ARPA can also detect solid waste in unreachable or hard-to-reach areas, as well as in courtyards and other private areas that would normally require a search warrant to investigate (and where they would go easily undetected).

Benefits also extend to the health and safety of officers. Inspections of illegal waste disposal sites indeed expose staff to the risk of contamination by pollutants (particularly asbestos, a common occurrence). As in most cases it is complicated or impossible to know in advance the kind of material on site, this further increases the risk of contamination. Preliminary assessment through satellite and aerial images allows instead for determining the nature of waste, and for adequately preparing the officers involved in inspections.

Finally, the application of AI and the level of accuracy guaranteed by the system allow for a significant reduction in the need for specialisation on the part of officers involved in waste inspections. Without the automatisation of detection through AI, satellite and aerial images must be analysed by a trained GIS expert. This is particularly time consuming and requires a level of expertise which would make the systematic, quarterly analysis of

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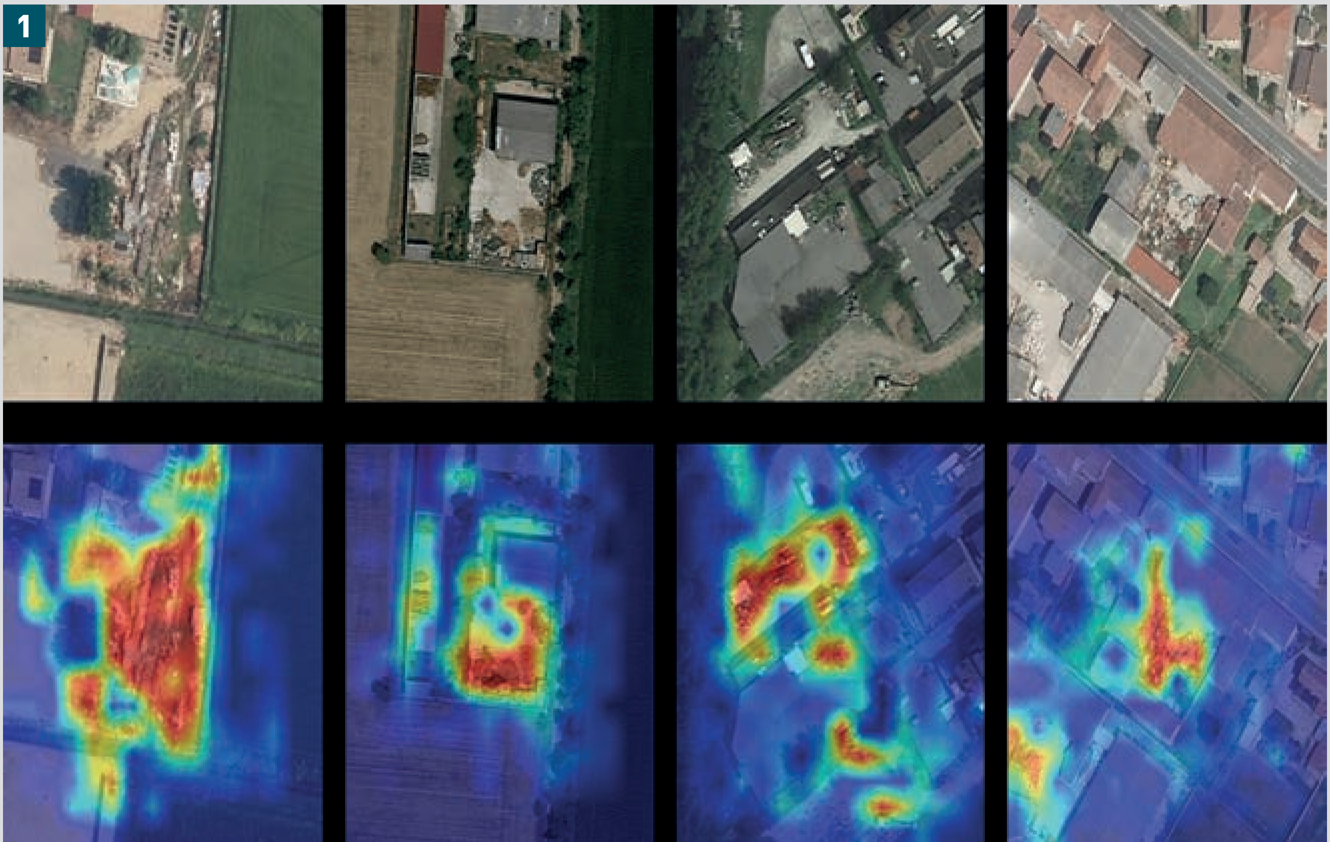

Two images showing the detection of possible illegal dumping sites at different magnitudes. Credit: POLIMI.

the territory, as performed by Polimi, almost impossible (Torres and Fraternali 2023).

9.3 OBSTACLES AND LIMITATIONS

The main issue affecting this application is the reliance on VHR RS images, whose availability is limited, and which are still relatively expensive, although their cost is decreasing – Polimi researchers estimate around 2,500 euros for each municipality, which covers an area of roughly 25 square kilometres. This does not represent at the moment a major issue for Polimi, since these data have been so far provided through the Copernicus Contributing Missions thanks to their participation in the Perivallon project. In the future, ARPA Lombardia will instead supply such images to Polimi thanks to an agreement between the two entities (Torres and Fraternali 2023). This however limits the potential expansion of the project beyond the current four municipalities in the Lombardy region, and the adoption of the application to partners with no access to the Copernicus Contributing Missions, or with limited budget.

In addition to this, the identification of different waste materials is not yet possible through satellite images, although this gap is narrowing thanks to new emerging technologies, and is instead only available for aerial images. While this is still an improvement compared to traditional monitoring, identifying potentially hazardous material already at the first stage of analysis could significantly improve field deployments (as they would prioritise the most contaminated locations), and further reduce the health and safety risks for officers.

9.4 REPLICABILITY

This application is considered highly replicable because of the ease in expanding the current system to other municipalities or regions in Italy, and because of the potential to generate similar tools fit for use in other countries.

Considering the first point, Polimi estimates that the expansion of the system in the areas surrounding the four municipalities will require little to no adaptation of the AI currently employed. The only major identified obstacle is the acquisition of images for other locations, which will require the involvement of other agencies like ARPA Lombardia, and a dedicated budget.

To expand the replicability in Italy, the IRIDE programme, an Italian earth observation initiative coordinated by ESA and ASI, financed with €1.07 billion, combining EU funds from Italy's National Recovery and Resilience Plan (PNRR) and national funds from the Complementary Plan (NCP), will provide the Italian public administration with free VHR images. Images can reach a resolution of < 1m for both optical and SAR images[85]. Notably, IRIDE explicitly lists monitoring of waste disposal and pollutant discharges among its target services. The outcomes of the use of the new constellation are still not certain at the time of writing, since the constellation will become active in June 2026; however, this could play an important role in increasing the replicability of systems such as the one developed by Polimi, which could be built with virtually no operational costs across the peninsula.

The replication of the model in other countries can be achieved thanks to the two datasets, one for aerial and one for satellite images, that Polimi has already built to allow for the training of other automated landfill discovery tools, which may be more suitable for different territories (Torres and Fraternali 2023). The two datasets are public and free, and feature more than 5,000 images each, divided into positive and negative examples (i.e., where a landfill is present, and where it is not). Positive cases are also anno-

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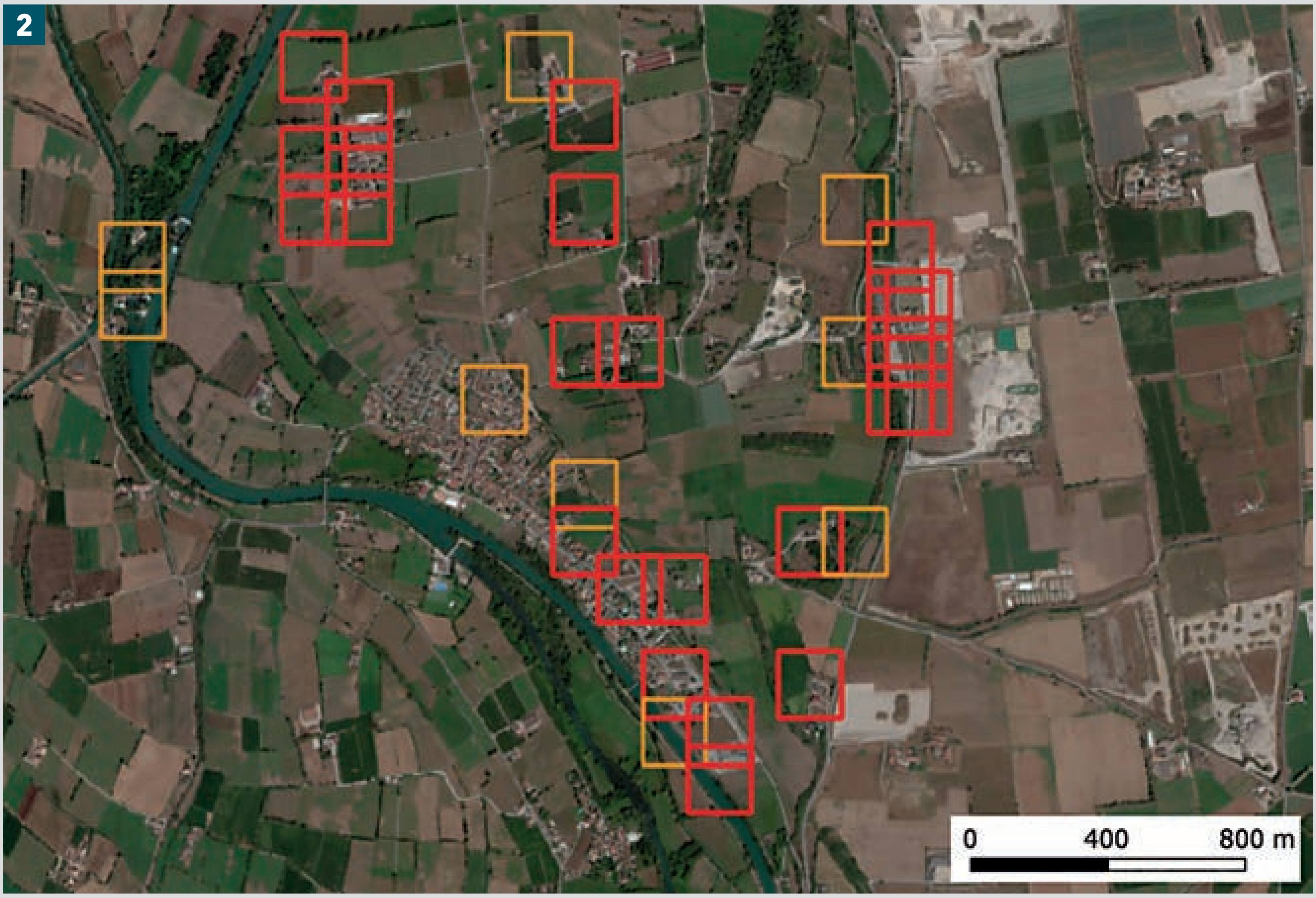

tated in most cases, and provide metadata about the type of waste, the kind of offenses, the kind of site considered and others. These two datasets are the first ever to be created, and could significantly advance the development of similar tools also in other parts of Europe, or even on other continents, since the issue of illegal waste disposal is one of the most frequent occurrences among environmental crimes worldwide.

84. See Perivallon website - Protecting the EuRopean territory from organised enVironmentAl crime through inteLLigent threat detectiON tools.
84. See ESA website - IRIDE satellites.

10. Using OSINT and EO to identify recent Illegal activities in northern Peru

Entity responsible for the analysis: United Nations Office on Drugs and Crime (UNODC), in cooperation with ESA - EO4SECURITY (international organisations)

Enforcement actor: Various Peruvian agencies, like DEVIDA (National Commission for Development and Life without Drugs), DIRANDRO (Anti-Narcotics Unit of the Police)

Topic: Illegal mining, illegal road construction, illegal logging and deforestation in convergence with other illegal activities

Status: Use case demonstration

Main sources of satellite data: Sentinel-1, Sentinel-2, Copernicus Contributing Missions

Replicability: High

All the information that is not otherwise cited has been provided by a representative of UNODC.

10.1 OVERVIEW

The UNODC office in Vienna combined open-source intelligence with Earth Observation data to analyse localised crimes that affect the environment. In partnership with ESA, several private companies and a research institute, information was gathered from traditional media, social media and multiple satellite sensors to document and interpret recent events[86]. One of the use cases focused on northern Peru, the border areas with Ecuador, Colombia and Brazil, where various illicit and criminal activities have serious impact on the local communities, the environment and the regional economy.

During the period from February to August 2025, the participating entities collected and analysed data in close interaction with experts of UNODC. An assessment was done of security-related incidents in and near the area of interest, like the prevalence of illegal mining, illegal logging, coca cultivation, drug production and trafficking, mentions of organised crime, violence and law enforcement actions. Two companies (Janes and Hensoldt) specialised in open-source data analysis collected data from traditional and social media that appeared in this period, leveraging key search words like M*inería illegal*, *Mercurio*, *Dragas*, *Cultivo de coca*, *Laboratorios clandestinos*, *Pistas clandestinas*, *Tala illegal*, *Tráfico de madera*, *Tráfico de especies*, etc. The searches were done in various languages – Spanish, Portuguese and English – and included spoken messages on YouTube and Facebook. All the events were gathered in a database and geolocated using geographic references in the messages. The geolocation was mostly done using descriptive references and not by directly extracting from the media itself (e.g., geolocated pictures or videos). In one case, the geolocation of an illegal mining site could be identified using the landscape features visible in the footage of a local news reporter on Facebook.

In parallel and in a coordinated manner, two additional entities analysed EO data for the study area. One of them (VITO) focused on mapping potential coca cultivation plantations by applying AI-based methods[87] to Sentinel-1 and Sentinel-2 imagery, complemented by meteorological (AgERA5) and topographical data (Copernicus DEM at 30m). The other agency (eGeos), also specialised in EO data, analysed satellite imagery at multiple scales. At a broad level, a forest cover loss layer from a dataset produced by the University of Maryland was used to assess deforestation trends, while for specific locations VHR sensors (Pleiades, Cosmo-SkyMed) were tasked to acquire new images during the monitoring period. COSMO-SkyMED Second Generation Spotlight images with very high resolution (60cm) were acquired at eight or 16 day intervals. By applying a Multi-Temporal and Coherence (MTC) analysis and an Amplitude Change Detection (ACD), heatmaps were produced that showed hotspots of transformative activities in the tropical vegetation. These detailed heatmaps made it possible to detect agricultural practices such as the clearing of forests for new coca fields, a strong indicator of the early stages of new coca plantations. In addition, the analysis of very high-resolution SAR and optical images provided detailed insight into the emergence, timing and extent of unregistered airstrips, mining machinery, logging areas and harvesting of coca fields.

10.2 BENEFITS

The combined analysis of open-source information and EO offers several advantages. The reports covering six months of data provided a near real-time overview of the prevalence of different illicit activities and their geographic distribution. Drug production, trafficking and seizures dominated the findings in the study area, followed by fuel trafficking. The geographic analysis showed that drug trafficking and illegal mining shared parts of the same supply chain, particularly for fuel and transport. This was evidenced by large fuel seizures – over 100,000 kilograms during one time period – which are essential for both gold mining dredges and drug trafficking logistics. Drug laboratories that were identified were located in forested areas near rivers, providing shelter as well as easy access and transport routes. Most of the seizures occurred near military bases or at checkpoints close to ports and small towns, locations that enable systematic

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Simple image of forests in Peru (first image), where the system automatically detected deforested areas (second image). Credit: EO4SECURITY and secure surveillance of river vessels. This pattern is understandable given the continued presence of illegal armed groups in the region.

Although there were numerous official reports, combining them with news and social media sources provided a deeper and more timely understanding of the events' context. For example, in the border area of Peru and Ecuador, several news reports described the construction of an illegal road leading to a new mining area. Across news and social outlets, local communities voiced concerns about the environmental degradation, declining water quality, public health risks, and what they perceived as insufficient or ineffective government intervention. Using EO data, the exact location was identified by leveraging VHR images, while free Sentinel-2 data made it possible to track the development of the 6 km-long road and the onset of large-scale mining activities. Using the time series, it could be proven that the reported destruction of the road did not prevent the heavy machinery from reaching the riverbanks over the following months. An EO classification of the image time series from 2024 to 2025 showed that the newly created mining sites occupied roughly 50 hectares in less than one year, with no indication that the expansion will slow down. Platforms like Amazon Mining Watch also provide a mapping product based on satellite images alone, but the new mining area at the border with Ecuador was only depicted in the last quarter of 2025 whereas this analysis showed that the large-scale mining along this river had already started one year earlier, in September 2024. This clearly demonstrates the value of combining OSINT and EO approaches to support timely interventions and to monitor the effectiveness of enforcement strategies.

10.3 OBSTACLES AND LIMITATIONS

Although news sites can be monitored relatively

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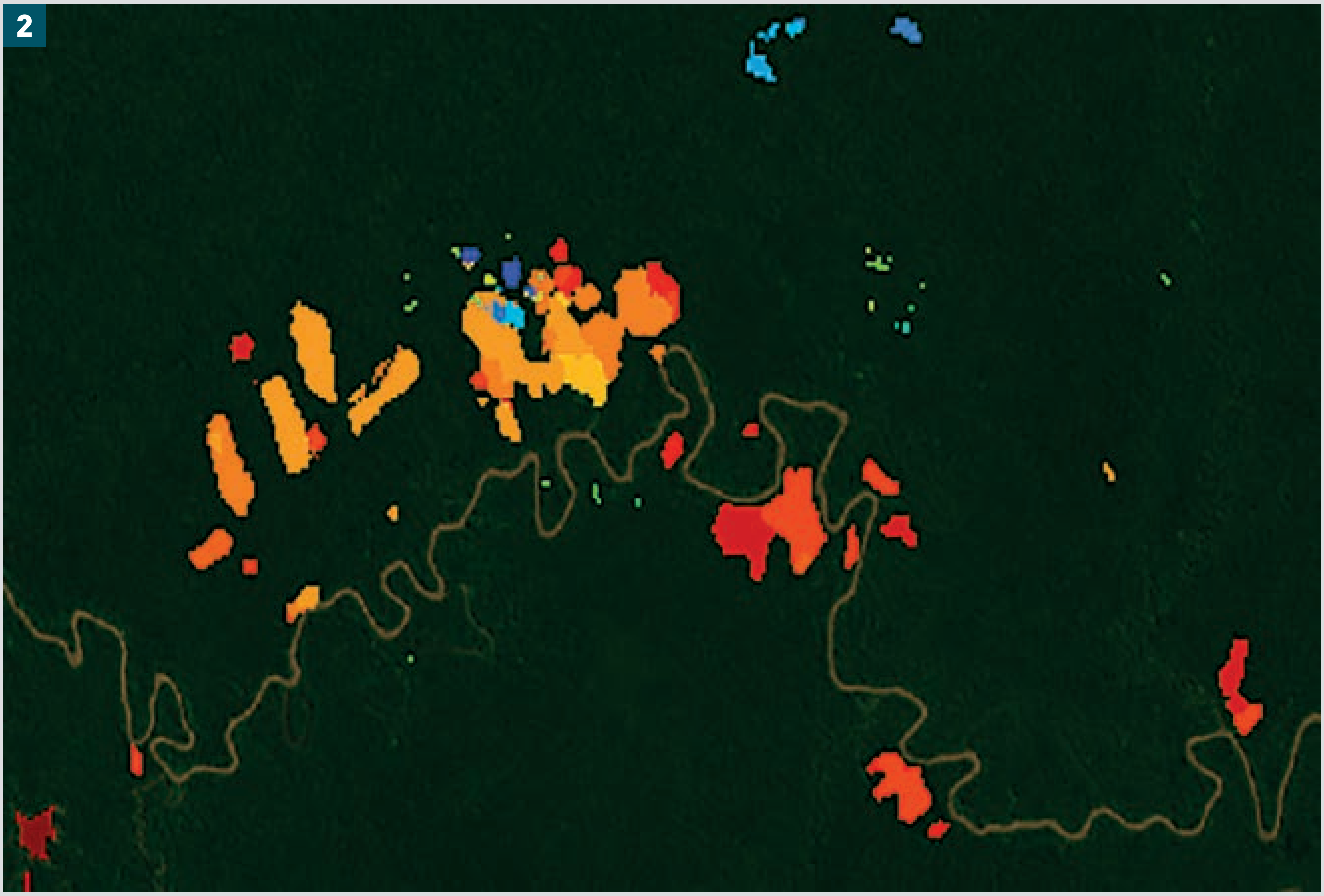

easily using RSS feeds, keywords and geographic filters, geolocating the reported events often still requires manual work – especially for illegal activities in remote natural areas like those in our study area. The analysis of spoken content in videos required specialised AI software and expert knowledge to process the data. However, in the very near future it is likely that a broader public will be able to build customised analytical pipelines using AI-powered APIs to perform similar analysis.

This use case demonstrated the added value of imagery with sufficient spatial resolution to detect early indicators of new roads, machinery, logging activity and emerging mining sites. The costs of VHR optical and SAR data can still be high, particularly when satellites must be tasked to acquire new images. Within the EO4SECURITY project, these images were obtained with the support of ESA; however, a broader uptake of this approach – which relies on a mixture of satellite sensors – will depend on the availability of affordable VHR images. It is encouraging that countries increasingly have access to such imagery, for example through the Peruvian government's contract with Airbus under the PeruSat-1 programme, which provides 1.5 meter resolution SPOT imagery.

10.4 REPLICABILITY

The methods used are highly replicable given the broad availability of news sites, social media content and EO data. In addition, geospatial platforms, free generic GIS software and accessible satellite data have become increasingly user-friendly, enabling a wider audience – not only specialists – to apply these tools. Such a connection between OSINT and EO is thus easily replicable using the model described in this application; adaptation will, however, be required to fit this approach to local conditions, data availability and the types of crimes in different countries, and to target the different criminal methodologies applied by different OCGs and other offenders.

86. EO4SECURITY project, funded by the European Space Agency and in cooperation with e-GEOS S.p.A., HENSOLDT Analytics, Janes and VITO.
87. Self-supervised feature extraction of multi-sensor pixel time-series to pixel embeddings, followed by the application of a CatBoost model to do coca mapping.

GLOSSARY

Earth Observation

- Earth Observation: The collection, analysis and interpretation of information about Earth's surface, atmosphere and oceans using various technologies such as satellites, aircraft and ground-based sensors[88].
- EO multispectral and hyperspectral data: An imaging or sensing system that captures a broad range of wavelengths across the electromagnetic spectrum with high spectral resolution, all outside the spectrum visible to the human eye. Unlike standard imaging systems that record colours in three or four bands (usually considered as multispectral), hyperspectral systems capture numerous narrow and contiguous bands, providing much more detailed information about the spectral characteristics of the observed objects[89].
- EO optical data: Data gathered through satellites using visible light, i.e., light spectrum visible to the human eye. Optical data are the most common type of data, and are what is generally intended by the general public as satellite imagery.
- EO platforms: Usually websites, apps or other online platforms where data elaborated by EO services can be accessed (as in the case of Copernicus Browser). Some platforms may also offer additional analytical tools (as in the case of the Global Nature Watch).
- EO product: A representation of a phenomenon that can be coded into information. A product serves multiple purposes and cross-domain applications. A characteristic of EO products is that they should undergo some data transformation to be considered decision-ready or inference-ready information[90].
- EO sensor: A specialised instrument or device that is designed to collect data from space and Earth's atmosphere. These sensors are equipped on satellites for various purposes, including Earth Observation, environmental monitoring and scientific research. Kinds of sensor vary, ranging from optical, which capture images of Earth's surface using visible and infrared light, to thermal and radio sensors, which use radio waves to detect and measure the properties of the Earth's surface[91].
- A service substantially based on EO data, provided by dedicated organisations or units, supplying products or information to be directly employed by final users.
- EO space data: All the information used in EO and obtained through satellite missions.
- Global Navigation Satellite Systems (GNSS): Constellations of Earth-orbiting satellites that broadcast their locations in space and time, of networks of ground control stations, and of receivers that calculate ground positions by trilateration. GNSS are used in all forms of transportation: space stations, aviation, maritime, rail, road and mass transit. Positioning, navigation and timing (PNT) play

88. See ESA: Earth Observation Glossary.
89. See ESA: Earth Observation Glossary.
90. See European Commission: Bioeconomy Glossary.
91. See ESA: Earth Observation Glossary.

a critical role in telecommunications, land surveying, law enforcement, emergency response, precision agriculture, mining, finance, scientific research and so on. They are used to control computer networks, air traffic, power grids and more. At present GNSS include two fully operational global systems, the United States' Global Positioning System (GPS) and the Russian Federation's GLObal NAvigation Satellite System (GLONASS), as well as the developing global and regional systems, namely Europe's European Satellite Navigation System (GALILEO), China's COMPASS/Bei-Dou, India's Regional Navigation Satellite System (IRNSS) and Japan's Quasi-Zenith Satellite System (QZSS)[92].

- In-situ observation (or ground observation): Data collected through a variety of systems and instruments on the ground, including observations from rangers, networked sensors and sampling of water or soil.
- Remote sensing: The process of collecting information about objects, areas or phenomena from a distance, typically using sensors or instruments that are not in direct physical contact with the target. This technology allows the observation, measurement and monitoring of Earth's surface, atmosphere and oceans from aircraft or satellites[93].
- Satellite mission: The deployment of satellites into orbit for various purposes, such as scientific research or providing different services, covering environmental, security or other purposes. Missions could be either single or constellation missions, i.e., involving multiple satellites.
- Spatial resolution: Distance between independent measurements, or the physical dimension that represents a pixel of the image[94].
- Spectral bands: Part of the electromagnetic spectrum of specific wavelengths. In remote sensing this is usually described by central wavelength and bandwidth[95].
- Synthetic Aperture Radar (SAR): A remote sensing technology that uses radar to create high-resolution images of Earth's surface. Unlike optical remote sensing techniques that rely on visible or infrared light, SAR works by transmitting radio waves towards Earth's surface and measuring the reflection of the waves. SAR is capable of imaging Earth's surface regardless of cloud cover, darkness or weather conditions. It is used for a wide range of applications, including mapping and monitoring of terrain, detecting changes in land use, measuring ocean currents and wave heights, and monitoring natural disasters such as floods and earthquakes. SAR has many civilian applications in fields such as agriculture, forestry and environmental monitoring[96].
- Temporal revisit: The interval between successive observations[97].

92. See United Nation Office for Outer Space: Global Navigation Satellite Systems (GNSS).
93. See ESA: Earth Observation Glossary.
94. See ESA: Earth Observation Glossary.
95. See EC-JRC: KCEO Glossary.
96. See ESA: Earth Observation Glossary.
97. See EC-JRC: KCEO Glossary.

Environmental crime

- Administrative law: The branch of law governing the creation and operation of administrative agencies.
- Automatic Identification System (AIS): An automatic system to indicate the position, course, speed and identification of vessels.
- Burden of proof: the legal standard that a party seeking to prove a fact in court must satisfy to have that fact legally established[98].
- Bycatch: The act of unintentionally fishing species that are not targeted by fishers, either because this is not allowed or is not of interest to them.
- Chain of custody: A recorded means of verifying where the evidence has travelled and who handled it before the trial[99].
- Civil law: A body of law diffused across Europe, which is based on legal codes and statutes.
- Civil penalty: A penalty, usually in the form of a monetary sanction, for not complying with the requirements of legislation or of regulations.
- Common law: A body of law diffused mainly in English-speaking countries and relying significantly upon judicial decisions.
- Concession area: Public land that national governments allocate to private or public developers for mining, agriculture or other uses.
- Crime convergence: The overlaps between different crimes, either of the same kind (i.e., different types of environmental crime) or of different kinds (the association of financial and environmental crimes, for instance). Overlaps happen in terms of players (i.e., the same players performing different crimes), time (for example trafficking of waste and illicit substances contemporarily) or place (deforestation, illegal mining and drug production happening in the same location, for instance).
- Criminal law: The branch of law sanctioning the perpetration of crimes and defining the criminal penalties against perpetrators.
- Dark vessel: A vessel of varying size that has deactivated its tracking instruments (or has none), frequently to conceal illegal activities.
- Environmental crime: Environmental crime covers the gamut of activities that breach environmental legislation and cause significant harm or risk to the environment, human health or both[100].
- Human intelligence (HUMINT): The practice of collecting and analysing information gathered from human sources, such as informants or interpersonal communication.
- Open source intelligence (OSINT): The practice of collecting and analysing information gathered from open sources, such as public media, the internet or commercial data, to produce actionable intelligence[101].
- Organised crime group: A network of people working together on structured and repeated criminal activities, with a local and/or an international focus.
- Selective cutting: The cutting of a

98. See Cornell Law School: Burden of Proof.
99. See National Institute of Justice: Legal Guide for the Forensic Expert.
100. See Europol: Environmental Crimes.
101. See European Data: What is OSINT: Open-source intelligence?

portion of the trees in a forest following different principles, such as economic (most profitable species), conservation (less relevant species for biodiversity) or silviculture.
- Ship-to-ship transfer: The act of transferring cargo from one vessel to another, either stationary or underway.
- Shipbreaking: The act of disposing of vessels once they reached the end of their life, usually dismantling them to obtain secondary raw materials and scrap.
- Tailings: A by-product of mining, consisting of the processed rock or soil left over from the separation of the commodities of value from the rock or soil within which they occur[102].
- Ultimate Beneficial Owner (UBO): The natural person who ultimately benefits from a business, a trade or other activities, such as trawlers and mines, even if he or she is not officially the owner.
- Vessel Monitoring System (VMS): A variety of different tracking systems designed to monitor fishing vessels.

ACRONYMS AND ABBREVIATIONS

AI Artificial intelligence
Ai2 Allen Institute for AI
AIS Automatic Identification System
ANB Agentschap voor Natuur en Bos
ASM Artisanal and small-scale mining
BISAG-N Bhaskaracharya National Institute for Space Applications and Geo-informatics
CBERS China-Brazil Earth Resources Satellite
CDSE Copernicus Data Space Ecosystem
CFP Common Fisheries Policy
CITES Convention on International Trade in Endangered Species
CMES Copernicus Maritime Surveillance Service
CNES Centre National d'Études Spatiales
COMIFAC Central African Forests Commission
CSA Canadian Space Agency
DETER Sistema de Detecção de Desmatamento em Tempo Real
DICAS Illegal Construction Detector
DLR Deutsches Zentrum für Luft- und Raumfahrt
DRC Democratic Republic of Congo
EDF Environmental Defense Fund
EEZ Exclusive economic zone
EFCA European Fisheries Control Agency
EGNOS European Geostationary Navigation Overlay Service
EIA Environmental Investigation Agency
EMPACT European Multidisciplinary Platform Against Criminal Threats

102. See UNDR: Tailings.

EMSA European Maritime Safety Agency
EO Earth Observation
EROS Earth Resources Observation and Science
ESA European Space Agency
EU European Union
EUDR EU Deforestation Regulation
FAO Food and Agriculture Organization
FISE Forest Information System for Europe
GI-TOC Global Initiative Against Transnational Organized Crime
GIS Geographic Information System
GMCP Global Maritime Crime Programme
GMES Global Monitoring for Environment and Security
GNSS Global Navigation Satellite System
GPS Global Positioning System
GWIS Global Wildfire Information System
HPG Historic Permanent Grasslands
HR High Resolution
HUMINT Human intelligence
IAI Istituto Affari Internazionali
IBAMA Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
IBM Indian Bureau of Mines
ICMBio Instituto Chico Mendes de Conservação da Biodiversidade
IMO International Maritime Organization
INPE Instituto Nacional de Pesquisas Espaciais
INTERPOL International Criminal Police Organization
ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale
IUP Indonesian mining exploration permit
IUUF Illegal, Unreported and Unregulated Fishing
LEA Law enforcement agencies
LEAF Law Enforcement Assistance for Forests
LEAP Law Enforcement Assistance Programme
LSM Large-scale mining
MAAP Monitoring of the Andean Amazon Project
MARPOL International Convention for the Prevention of Pollution from Ships
ML Machine learning
MODIS Moderate Resolution Imaging Spectroradiometer
MSS Mining Surveillance System
NASA National Aeronautics and Space Administration
NCEI National Centers for Environmental Information
NEXRAD Next Generation Weather Radar
NGO Non-Governmental Organisation
OCG Organised Crime Group
OSINT Open-Source Intelligence
POLIMI Politecnico di Milano
PPCDAm Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal
PRODES Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite
PROFEPA Procuraduría Federal de Protección al Ambiente
QGIS Quantum GIS
RADD Radar Alerts for Detecting Deforestation
RBI Topographic Map of Indonesia

REE Rare earth elements
RPAS Remotely Piloted Aircraft Systems
RUB Registro Único de Beneficiarios Finales
SANParks South African National Parks
SAR Synthetic Aperture Radar
SEPRONA Servicio de Protección de la Naturaleza
SIFAC Système d'Information Forestier d'Afrique Centrale
SLE Small Landscape Elements
THETIS The Hybrid European Targeting and Inspection System
UAV Unmanned Aerial Vehicle
UBO Ultimate Beneficial Owner
UN United Nations
UNDP United Nations Development Programme
UNEP United Nations Environment Programme
UNFCCC United Nations Framework Convention on Climate Change
UNICRI United Nations Interregional Crime and Justice Research Institute
UNODC United Nations Office on Drugs and Crime
USGS United States Geological Survey
VHR Very High Resolution
VMS Vessel Monitoring System
WRI World Resources Institute
WWF World Wide Fund

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INTERVIEWS

This list includes all interviews conducted as part of the research for the Main Analysis and the Sectorial Analysis. Interviews conducted to gather additional information for the case studies are cited individually in each case study.

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Multispectral image of Valparaíso, Chile, focusing on the valleys where illegal water abstraction for avocado and marjuana production is a common occurrence. Contains modified Copernicus Sentinel data (2024), processed by ESA.