Harnessing technologies to combat environmental crimes: the potential of satellites, drones, water sensors and super-resolution imaging

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Abstract

Preventing and tackling environmental crime is a global priority. The multiple risks this phenomenon poses, the high-profit margins, the low risk of detection and prosecution, and the notable lack of empirical research on specific investigative practices call for innovative approaches to evidence gathering and analysis to ultimately increase the effectiveness of the fight against waste-related environmental crime.

This article investigates the use of co-creation approaches to identify practitioners' needs in the field of waste-related environmental crimes, and it attempts to shed light on the range of solutions that technology can offer to improve environmental crime detection, investigation and prosecution. These include satellite, drone and sensor technology, as well as the integration of remote sensing (RS) technologies enhanced with machine learning (ML). The article concludes by arguing that the further employment of available super-resolution (SR) techniques can unlock the potential for more detailed environmental monitoring and analysis and is valuable for both image classification and segmentation tasks.

Keywords: waste crime, river pollution, police investigations, law enforcement agencies, Earth observation.

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Introduction

'Waste crime', a term encompassing a spectrum of illegal activities within the waste management cycle, poses significant environmental and public health risks (Walters and Loureiro, 2020). These activities range from the production of waste materials to their storage, transport, disposal and reuse (Baird et al., 2014). Common forms of waste crime include trafficking, dumping, mismanagement of waste and water, and air pollution (Buczma, 2020). The motivations behind waste crime are typically lucrative profits and the perceived low risk of detection or prosecution (Interpol, 2022).

Technological advancements offer promising avenues for improving waste crime detection, investigation and prosecution. Drones and satellites, for instance, enable efficient surveillance and data collection over large areas, aiding in identifying illegal waste disposal sites and monitoring environmental violations. However, despite recognition of this in the literature (Alderuccio et al., 2019; Di Fiore et al., 2017; Lega and Teta, 2016; Mager and Blass, 2022), the integration of these technologies into law enforcement practices remains limited.

This article presents an approach implemented with practitioners in the field of waste-related environmental crimes to identify their operative needs and skills gaps. It explores how technological solutions can bolster practitioners' efforts against waste crimes by supporting the investigation, forensic practices and detection of waste crimes.

Following an extensive literature review, the article firstly presents the results of gaps and needs analysis conducted within the scope of the EU-funded project Environmental crimes' intelligence and investigation protocol based on multiple data sources (Emeritus) ([2]), with a representative sample of law enforcement agencies (LEAs) and other operators involved in waste-related environmental crimes. The information collected during this phase is then used to tailor relevant technological solutions to support investigative practice. In this regard, the article presents the case of using SR techniques to enhance satellite images, thus facilitating the identification of illegal waste dumping and/or storage sites.

Literature review and current state of the art

Criminal activities related to waste often involve organised criminal groups, particularly in cases of transnational trafficking (Andreatta and Favarin, 2020). Despite its detrimental effects, waste crime remains a low-risk venture, largely due to deficiencies in law enforcement capabilities and prioritisation (Europol, 2013). Moreover, environmental investigative teams in LEAs lack specialised resources, while multilateral LEAs' operations to tackle waste crime are perceived as lower priority vis-à-vis those to combat 'mainstream' crimes (Eurojust, 2014).

Technological advancements can help improve investigative practices in several ways. For instance, the advancement of Earth observation (EO) technology can transform environmental monitoring. Indeed, satellite and aerial images offer wide-scale perspectives unattainable by ground methods, thus offering great potential for detecting and combating illegal waste disposal.

Aerial imagery, the initial application of which dates back 40 years, when it was employed to estimate waste in neighbourhoods in Tampa, Florida (Garofolo and Wobber, 1974), can also better and more efficiently identify waste deposits. Despite the increasing applications of these methods over time, challenges arose due to the high costs and infrequent revisit intervals associated with aerial photogrammetric flights.

The field saw a significant shift in digital photogrammetry that enabled the creation of high-resolution (HR) digital terrain models to assess changes in waste deposits over time (Vincent, 1994). As technology progressed, satellite imagery began to supplement aerial imagery, offering wider coverage and better frequency. A notable example was the use of QuickBird images to identify illegal waste activities in the United Kingdom (Purdy et al., 2017). The success of segmentation algorithms in change detection relies on the spatial and spectral resolution of satellite imagery, which ensures detailed ground feature representation and the capture of unique material properties.

Projects such as the Life Smart Waste project ([3]), AI Visions' AI for Good – Landfills project ([4]) and the European Space Agency's Wastemon Project ([5]) highlight the growing trend of integrating satellite data with ML to enhance waste dump detection and monitoring. Recent studies have emphasised the importance of segmenting very high-resolution (VHR) imagery for waste detection. Advances in deep learning (DL) have notably enhanced satellite image segmentation methods. Techniques like convolutional neural networks (CNNs), which use multiple non-linear layers for feature extraction and transformation, are now key in both supervised and unsupervised learning scenarios (Chen et al., 2021). These models, which integrate DL with computer vision, were effective in solid waste management applications (Ganci et al., 2021). Advancements in satellite sensors brought an influx of HR images, which are crucial for detecting illegal waste dump sites (Notarnicola and Anguilli, 2004). CNNs, particularly those using Edge Boxes and multilayered neural networks, demonstrated effectiveness in detecting targets in satellite images of varying sizes and orientations (Kattenborn et al., 2021).

While VHR imaging shows great promise in monitoring waste dumping, challenges remain, mainly due to the high costs of commercial data. Additionally, end users have repeatedly noted the need to detect illegal waste sites as large as 0.5 hectares, a task not feasible with only medium-resolution imagery. Applying SR algorithms to Sentinel-2 data, a freely accessible medium-resolution imagery source, is an emerging solution that allows the enhancement of images capped at a 10 m resolution, aiding in monitoring dynamic features, environmental changes and disaster response. The super-resolution convolutional neural network is a DL model that has improved the spatial resolution of satellite images (Müller et al., 2020). Moreover, the enhancement of older and current datasets can offer more detailed insights, improving long-term environmental assessment accuracy.

In addition, satellite technology, equipped with high- to medium-resolution optical and thermal imagery, revolutionised the monitoring of environmental crimes. Thermal satellite imagery can detect elevated land surface temperatures, revealing illegal waste sites and waste burning. Additionally, synthetic aperture radar (SAR) satellite imagery can detect changes in land topography, sewage and chemical spills, indicating illegal waste disposal.

Finally, drones have enabled significant progress in waste management by complementing satellite technology. They provide HR and multiband imagery and can be remotely controlled or autonomously perform pre-programmed routes. Furthermore, several drones can work collaboratively, sharing tasks and data to scan an area, hence reducing monitoring time.

Overview of Emeritus technologies to fight environmental crime

The combination of several of the technologies mentioned above is one of the core aims of the EU-funded Emeritus project, which is to ultimately improve LEAs' effectiveness in the identification, location and collection of evidence about environmental crimes.

Indeed, satellite and drone technology is integrated with ML, enabling systems to learn and adapt without explicit instructions to automatically detect and classify different environmental violations, further enhancing LEAs' capabilities to identify offenders. Emeritus also employs DL models, particularly CNNs, that have been a game changer in image processing, being able to learn and excel at visual tasks like object detection, image fusion, scene classification, and land use and land cover classification in RS image analysis (Youme et al., 2021).

In addition, optical cameras and/or satellite monitoring, along with computer vision algorithms, are combined to tackle river pollution, which endangers the environment and human health. Determining river contaminant sources is crucial for investigations, but, when released into a river, contaminants swiftly disperse due to turbulent mixing and molecular diffusion (Wang et al., 2023). To limit the related damage, it is vital to quickly identify contaminant sources (Kwon et al., 2021). Emeritus goes one step further by enhancing the development of more powerful detection tools using water quality sensors that can detect variables, including pH levels and changes in chemical composition, extending beyond basic monitoring to identify pollution sources.

Methodology

Within the framework of Emeritus, a design-thinking inspired methodology has been used to co-create, with LEAs and border guard (BG) authorities involved in the project's consortium, a set of tools to improve efforts to tackle waste-related environmental crimes. Design thinking is an iterative process for human-centred innovative design of products and solutions, with the most well-known version defined by the Hasso Plattner Institute of Design at Stanford University[6]. This approach seeks to understand users' perspectives and needs to challenge typical assumptions and define original human-centred solutions.

This methodology encompasses five (non-linear and iterative) steps, namely: (1) empathise, (2) design, (3) ideate, (4) prototype and (5) test. The present section provides an overview of the approaches implemented to cover all the stages of this process, from understanding needs and challenges (corresponding to steps 1 and 2) to ideation, prototyping and testing of new solutions (corresponding to steps 3, 4 and 5). In particular, it presents the methodologies used to (1) identify the main factors hampering the uptake of cyber-physical technologies by practitioners in the field of environmental crime, (2) define the most significant gaps and needs in responding to environmental crime and (3) ideate and prototype SR models for enhancing the detection of waste dumping.

Procedural challenges and barriers

Interviews were conducted with the LEAs and BGs authorities involved in Emeritus to identify the main factors hampering the uptake of cyber-physical technologies such as drones, satellites and sensors by practitioners in the field of environmental crime. LEAs and BGs authorities (from Greece, Italy, Moldova, Romania and Spain) identified three main factors, which are presented in the section 'Procedural challenges and barriers' below, under 'Results and discussion'.

Training needs assessment

The Emeritus training needs assessment (TNA), involving both internal and external practitioners, was conducted through focus groups in five European countries (Greece, Italy, Moldova, Romania and Spain), following a dedicated methodology designed by the project's partner CIFAL Malaga to gather information on training needs in the area of environmental crime. This involved identifying six main questions and presenting these to focus group participants using Google Forms', as shown in Figure 4.1.

1. Please indicate the institutions or organizations the members of this focus group belong to.
2. Do you think a project of this type is necessary? Do you think it is beneficial for our region and for your institution? Why?
3. Do you regularly attend training on this subject? If so, who gives them (your own institution, university, etc.)?
4. What are your training needs on this topic? Which topics, within the field of environmental crime, are of interest to you?
5. Is there currently a coordination body or system among all the institutions engaged into environmental crime?
6. Is there any other organization/institution with responsibility or interest in environmental crime that has not been invited to this focus group today?

Figure 4.1. List of questions for Emeritus TNA. Source: The author.

The proposed agenda for the focus groups included an introduction to the project for the participants, their possible role in it, the benefits of the project and proposed training, which was planned to be delivered based on the identified needs. CIFAL Malaga suggested each focus group last at least 4–5 hours and be attended by a heterogeneous group of national stakeholders (police, non-governmental organisations, academia, environmental agents, coastal guards, etc.).

Super-resolution techniques for image classification

Illegal landfills are a pressing issue with significant environmental, economic and public health implications. Despite AI and computer vision advancements, it is still challenging to train robust ML methods for waste detection because they need abundant aerial images of potential illegal landfills. Existing aerial landfill datasets are scarce and typically lack location information due to confidentiality agreements (Torres and Fraternali, 2023). Additionally, open-access satellite image banks like Sentinel-2 and Landsat via Copernicus ([54]) typically provide low-resolution images with no information about potential illegal landfills.

To address the quality issue, this article proposes to use SR techniques to generate an HR version of a given low-resolution image (Kim et al., 2016 a, b). Consequently, this study undertakes a thorough assessment of waste detection algorithms, representing the first exploration of SR enhancement and cross-domain evaluation within the Emeritus project. The methodology applied uses the HR dataset for image classification, assessing its performance across various resolutions. The goal is to evaluate how a model trained on HR images performs when applied to downscaled samples.

([54]) The EU's Earth observation programme (https://scihub.copernicus.eu/).

Super-resolution techniques for image segmentation

To overcome the low spatial resolution of freely available imagery, this article proposes to exploit enhanced Sentinel-2 imagery in waste analysis. The advancements in SR techniques, with current techniques that can reconstruct HR details from low-resolution images, unlock the potential for more detailed environmental monitoring and analysis (Fernandez-Beltran et al., 2017). The integration of SR models with existing segmentation models, notably the combination of DeepLabV3+ and a ResNeSt101 encoder, has led to a significant improvement in identifying waste dump sites from Sentinel-2 imagery.

This approach is particularly valuable due to the limited availability of HR imagery and labelled datasets specifically designed for waste dump identification. While previous studies often relied on VHR imagery, this may not always be feasible or cost-effective. The successful use of SR techniques with Sentinel-2 data, a freely accessible medium-resolution imagery source, offers a more accessible and scalable solution for waste dump identification.

Results and discussion

Procedural challenges and barriers

Following the methodology presented in the section 'Procedural challenges and barriers' above (under 'Methodology'), practitioners in the field of environmental crime identified three main factors as major constraints to the uptake of cyber-physical technologies: procurement-related factors, administrative/procedural aspects and resource shortage.

Regarding procurement-related factors, two critical elements were highlighted: technology cost and the administrative burden of procurement. While the first is expected to decrease over time due to technology consolidation, the latter poses a challenge. Being public entities, LEAs and BGs are subject to the procurement rules dictated by EU regulations and national authorities to guarantee the transparency and legitimacy of the public acquisition process. However, such rules hamper or even prevent the use of such technologies within investigation procedures. Common concerns include the requirement for permits, uncertainties about data storage, and the centralisation of the deployment decision. For instance, drone usage in the European urban environment is regulated by European Union Aviation Safety Agency (EASA) rules implemented by Member States, requiring a case-by-case assessment. Specific authorisations of deviations from standard aeronautical scenarios or limitations on overflying people may impede drone usage, especially among organisations lacking the internal expertise to evaluate aeronautical rules comprehensively.

In addition, procedural concerns arise regarding the admissibility of digital or cyber-physical evidence in court, as well as their collection and secure storage. Satellite and drone data brought to court cannot stand alone but require supporting metadata (i.e. acquisition data and time, location, source, etc.), and, given the rise of generative AI, it is vital to protect collected digital evidence against alteration and corruption.

Finally, resource shortage is a baseline common issue entailing limited experienced drone operators and the availability of drones and/or other relevant digital devices.

Training needs assessment

Environmental crime is complex in terms of definition, scope, legal framework, impacts, drivers and connections with other serious offences. Identifying and understanding the current barriers is critical to addressing such crimes. The most significant gaps in responding to environmental crime, identified through the United Nations Environment Programme's expert process (UNEP, 2018) and reinforced by the Emeritus project, relate to four issues.

The first is a lack of data, knowledge and awareness: the paucity of publicly available data on environmental crimes and related issues causes difficulties for governments and public organisations attempting to develop effective policies to combat such crimes.

The second issue is the insufficient and restricted application of legislation, primarily due to limited legal and administrative knowledge among LEAs. This results in personnel not being fully aware of their enforcement authority, the legal responsibilities related to evidence collection, the use of complementary laws, and how and to what extent information should be shared internationally.

The third issue is the lack of capacity across the entire enforcement chain of investigators, prosecutors and judges, which inhibits frontline forces responsible for combating environmental crime. This is marked by deficiencies in the necessary knowledge, training and equipment to prevent environmental crimes and the need for more sophisticated law enforcement capacity.

The fourth issue is insufficient national and international cooperation and information sharing among authorities. This limitation stems from factors such as competition, mistrust and the absence of clear institutional frameworks, hindering effective resource utilisation for combating environmental crime.

Furthermore, the Emeritus TNA revealed that countries have different levels of training in environmental crime: many provide training, but this is mostly general or theoretical. Many participants declared interest in receiving training in legislative matters – for example definitions of environmental crimes, codification of legislation, and damage calculations – and on the uses and applications of cyber-physical technologies in their daily activities. A frequency-based graph (Figure 4.2) presents the most prominent training needs across the following categories:

— legal: environmental crime identification, contaminating levels, cadastre legislation, environmental legal framework;

— ecosystemic services: measuring environmental damage to flora, fauna, water, air and soil; effluent sampling, dumping waste, forest fire prevention and control;

— procedure: capping co-competent institutions, environmental crime reporting protocol, geo-profiling;

— tech: drone handling, satellite analysis, early fire detection, forest video surveillance, sensors, new tech (AI, big data, etc.).

Figure 4.2. Emeritus TNA results. Source: The author.

Figure 4.2 shows that, according to Emeritus TNA participants, the tech domain, that is, technological tools to prevent, detect or mitigate potential environmental crimes and their associated impacts, is the most prominent one in terms of training needs. The legal domain, namely environmental crime identification, the EU legal framework and cadastre legislation, also scored highly in the Emeritus TNA, suggesting the need for participants to acquire more specialised legal and administrative knowledge in the field of environmental crime.

Finally, the Emeritus TNA revealed that participants are, on average, aware of the procedures to be followed when a potential environmental crime is detected (procedure domain), as well as the procedures for sampling, data analysis and assessment of environmental damage to an ecosystem (ecosystemic services).

Super-resolution techniques for image classification

Following the approach detailed in the section 'Super-resolution techniques for image classification' under 'Methodology', we outline a comprehensive evaluation protocol in the field of waste detection via image classification that, to the best of our knowledge, represents a novel and unexplored avenue. Our initial results indicate the possibility of improving performance classification in a cross-domain setting with SR enhancement. Furthermore, we conduct a thorough analysis of various metrics to gain a comprehensive understanding of how these models can be tailored to specific domains.

Figure 4.3. Examples of images (from left to right) showing our SR enhancement: the input image, before SR enhancement (low resolution), the output image (following SR enhancement) and the ground-truth (HR) image. Source: The author.

Figure 4.3 shows an example of applying SR techniques to a sample from the AerialWaste dataset (Torres and Fraternali, 2023), comparing the original HR sample (right) with the result of applying SR techniques (middle) to the low-resolution version (left).

Super-resolution techniques for image segmentation

The author's contribution to this evolving field has so far consisted of developing a library of 18 state-of-the-art SR models that were tested in different scenarios relevant to the study of waste (Selea et al., 2023). This library, illustrated in Figure 4.4, encompasses a diverse array of neural network architectures, including sophisticated generative adversarial networks (GANs), known for their ability to generate high-quality, detailed images (Saxena and Cao, 2021); CNNs, which excel in capturing spatial hierarchies in image data (Chen et al., 2016); and residual networks (ResNets), which address the vanishing gradient problem effectively and allow for deeper and more accurate networks (He et al., 2016).

These models were trained using a vast dataset of medium-resolution images (Sentinel-2), together with VHR imagery (SPOT), to systematically upscale medium-resolution data to generate their HR equivalents. The training methodologies employed were cutting edge, involving adversarial training that pits two networks against each other to improve generated image quality, feature extraction that captures essential details from low-resolution images, and residual learning that helps construct the HR output by learning from the residuals of the low-resolution input.

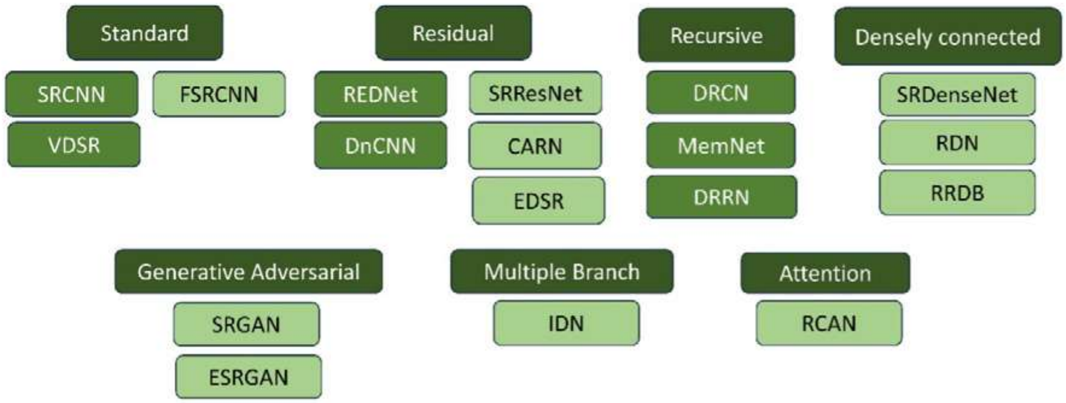

Figure 4.4. Overview of the library of SR models implemented for SR. Source: The author.

NB: CARN, convolutional anchored regression network; DnCNN, denoising convolutional neural network; DRCN, deeply recursive convolutional network; DRRN, deep recursive residual network; EDSR, enhanced deep super-resolution; ESRGAN, enhanced super-resolution generative adversarial network; FSRCNN, fast super-resolution convolutional neural network; MemNet, very deep persistent memory network; RDN, residual dense network; RRDB, residual in residual dense block; SRCNN, super-resolution convolutional neural network; SRGAN, super-resolution generative adversarial network; VDSR, very deep super-resolution. RedNet, residual encoder-decoder network. SRResNet, super-resolution residual network. SRDenseNet, super-resolution dense convolutional network.

This library represents a technical achievement while also serving as a resource for enhancing Sentinel-2 data. By applying these SR models to Sentinel-2 imagery, we can significantly improve resolution, making it possible to discern finer details and enhance the detection and differentiation of illegal waste sites.

In our activities associated with the Emeritus project, we have taken the first steps in integrating our own pre-existing SR libraries with segmentation models. We focused on applying DL-based segmentation directly to Sentinel-2 data to identify waste dump sites. This task required the segmentation models to differentiate between various land covers and to outline the areas of interest precisely. To train these models, we created a unique dataset with manually labelled masks, a necessary step due to the lack of suitable open-source datasets for this specific application.

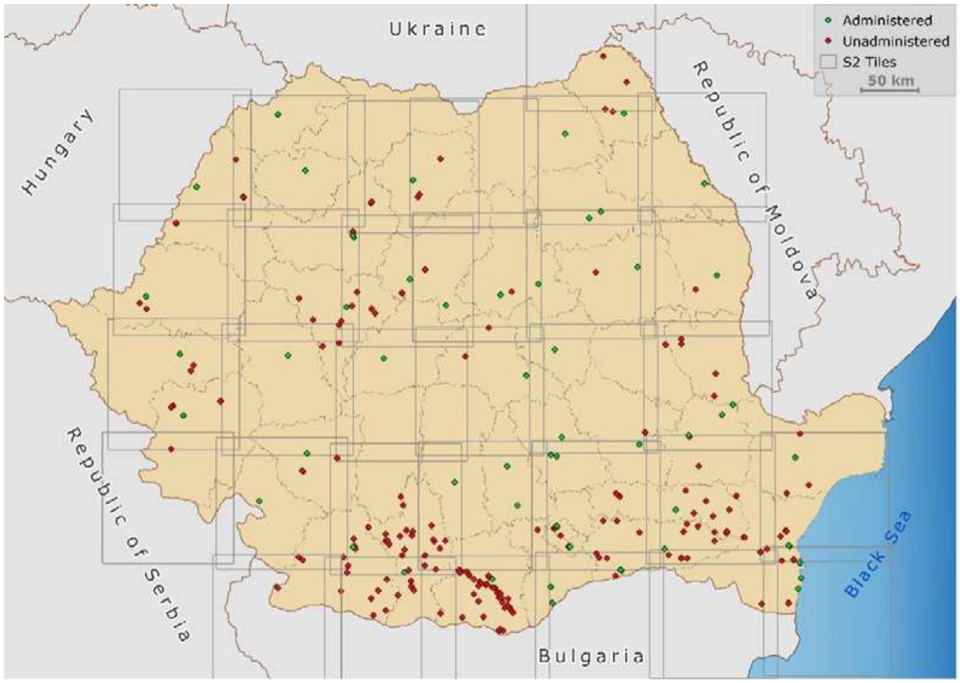

Figure 4.5. The training dataset for segmentation encompasses a total of 159 administered and 495 unadministered sites from 2020 to 2022. Source: The author.

Through extensive experimentation and optimisation, including hyperparameter tuning facilitated by the Optuna framework (Akiba et al., 2019), we determined the most effective combinations of models and encoders for our segmentation task. The standout combination was the DeepLabV3+ (Du et al., 2021) model paired with the ResNeSt101 (Zhang et al., 2021) encoder. When applied to Sentinel-2 data, this pairing achieved a validation intersection over union score of 0.6, signifying a 60 % accuracy in matching the predicted masks with the actual waste dump locations. The testing dataset yielded an intersection over union score of 0.5 and a precision rate of 0.8, confirming the model's capability to generalise well to unseen data.

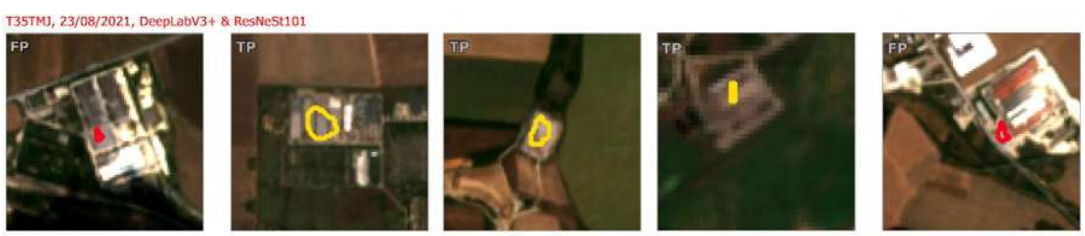

Figure 4.6. Inference results on different dates from a Sentinel-2 tile in Romania, showing false positive (red) and true positive results (yellow). Source: The author.
NB: FP, false positive; TP, true positive.

These findings highlight the potential of SR techniques in addressing the limitations of medium-resolution imagery for waste dump identification. By enhancing the resolution of Sentinel-2 data, finer details become discernible, leading to improved differentiation of waste dump sites from other land cover types. This not only contributes to the advancement of waste management practices but also aligns with the broader objective of leveraging EO data for environmental monitoring and sustainable development.

Further development and refinement of SR techniques hold the promise of even more precise identification of smaller and less regular waste dump sites, which are currently challenging to detect due to the limitations in spatial resolution. By continuously improving these techniques and expanding their application to diverse geographical contexts, the capacity to monitor and address in a less costly manner the global issue of waste management can be significantly enhanced, contributing to a more sustainable and environmentally conscious future.

Conclusion and outlook

This article attempted to shed light on the range of solutions that technologies can offer for enhancing the detection, investigation and prosecution of waste crimes, a serious global issue with significant environmental, economic and public health implications.

The article first provided an overview of the technologies and techniques Emeritus employs in fighting environmental crime. These include satellite, drone and sensor technology, as well as the integration of RS technologies with ML, which enables systems to learn and adapt without explicit instructions to detect and classify different environmental violations automatically.

The article then presented the main procedural challenges and barriers limiting the uptake of cyber-physical technologies by practitioners and the most significant gaps in responding to environmental crime identified through the United Nations Environment Programme's expert process and reinforced by the outcomes of the Emeritus TNA. The article then demonstrated that EO technology advancement, including better satellite and aerial imaging, can transform environmental monitoring by offering wide-scale perspectives unattainable by ground methods.

We concluded by suggesting that the further employment of available SR techniques able to reconstruct HR details from low-resolution images can unlock the potential for more detailed environmental monitoring and analysis, and is valuable for both image classification and segmentation tasks.

As we look to the future, we are poised to take the following step: apply the described SR models to Sentinel-2 data to further enhance image resolution and, consequently, the accuracy of waste dump identification. This will involve transferring the segmentation methodology to the super-resolved imagery. By doing so, it is expected to achieve even more precise identification of smaller and less regular waste dump sites, which are currently challenging to detect due to the limitations in spatial resolution of Sentinel-2 data.

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