Stolen Heritage
Multidisciplinary Perspectives on Illicit Trafficking of Cultural Heritage in the EU and the MENA Region
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Satellite Technologies for Monitoring Archaeological Sites at Risk

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Abstract Satellite technologies are increasingly used to track looting in remote and inaccessible archaeological sites and assess damage to heritage. Evidence gathered in our study proves a growing user uptake of these technologies, beyond the specialist remote sensing community, but also that a more synergistic use of optical and radar data is required. The advantages of such an approach to satellite monitoring are demonstrated on Apamea, Syria. Current limitations and future perspectives are outlined, as an entry point to a comprehensive review published by the authors in the referenced journal article, that the readers are encouraged to refer to for a more in-depth and specialist discussion.

Keywords Looting. Archaeological remote sensing. Satellites. Change detection. Feature extraction. Pattern recognition. Google Earth. Synthetic Aperture Radar. Sentinel-2. COSMO-SkyMed.

Summary 1 Introduction. – 2 State of the Art and User Uptake. – 3 Synergy Between Optical and Radar Satellite Technologies. – 4 Multi-temporal and Multi-sensor Monitoring at Apamea, Syria. – 5 Limitations and Future Perspectives.

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1 Introduction

'Looting', defined as illegal excavations through digging holes on a site of archaeological or historic significance – usually in areas yet unexcavated by archaeologists – is an anthropogenic phenomenon that can be triggered and driven by various economic, social, cultural, and political factors (e.g. Al-Quntar 2013). Especially in poor regions, looting may be on a small scale, mainly for subsistence (e.g. Hamdani 2008). Large-scale excavation by means of digging tools and machinery is a planned activity, run by well-organized groups (Marrone 2018). Such systematic looting by means of earth-moving machinery can spread in a short time across a whole archaeological site, cause irreversible damage to the pristine archaeological stratification and context, and distinctively pock-mark the landscape. Data collected from space can provide a mean to capture this effect, although some limitations may apply depending on the visibility of the looting features, i.e. if they are located in areas obscured to the satellite line-of-sight, are covered by accumulated sediment, within structures and buildings, or dug as tunnels and holes along slopes.

When no visibility issues are present, satellites are helpful in documenting looting owing to the peculiar features that it leaves on the ground. These are common across different geographic locations. Looting pits distinctively differ from other types of archaeological features, and their excavation completely modifies the surface morphology of the affected landscape. Hand-dug pits are frequently scattered or clustered in small groups, characterized by shallow depth, and surrounded by mounds of debris that is sifted and then accumulated aside. Machine-assisted looting generally manifests in the form of regular, highly concentrated and extended series of looting holes, and sometimes includes excavation trenches a few meters deep.

While in the past archaeologists and heritage conservators documented looting features during their field inspections, through airborne surveys (e.g. Stone 2008) and more recently via drones (e.g. Kersel, Hill 2015), since the early 2000s there has been an increased and more systematic use of satellite images, mostly sourced from commercial providers (e.g. DigitalGlobe) or freely accessible platforms (e.g. Google Earth; Contreras 2010). The satellite-based assessment allows archaeologists to successfully overcome limitations of site inaccessibility and substantiate incident reports collected from broadcast and social media, or written based on ground observations. In this regard, there is a consensus within the research community about the advantageous properties offered by satellite imagery (e.g. Bewley et al. 2015; Danti, Branting, Penacho 2017; Rayne et al. 2017; Tapete, Cigna 2018).

Undoubtedly, some events accelerated the use of satellite imagery for detecting looting, such as the Syrian conflict during which remote

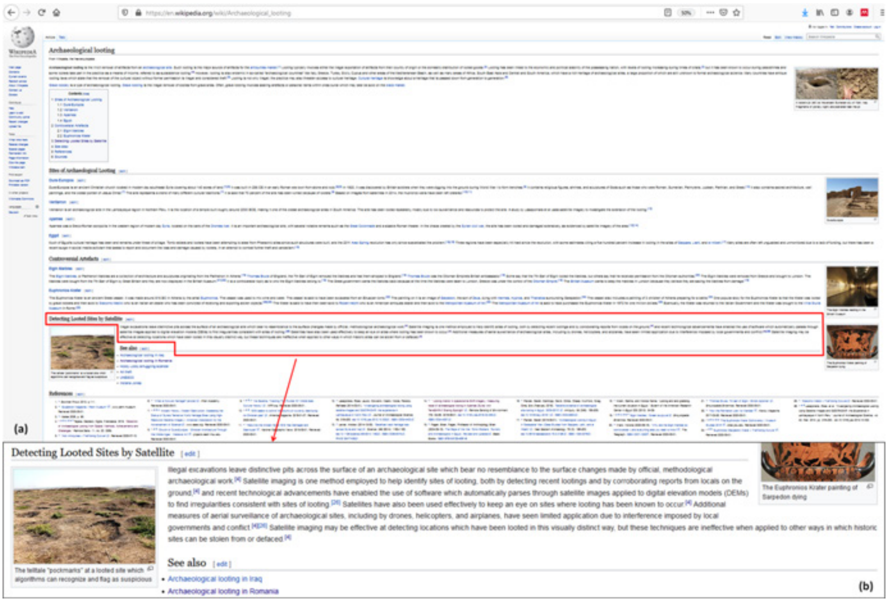


Figure 1 (a) Wikipedia, "Archaeological looting" webpage and (b) the section dedicated to the use of satellites for detection of looted sites (last edited on 22 November 2020). Wikipedia, Creative Commons Attribution-ShareAlike License

sensing data have come of age for archaeological purposes (Brodie, Sabrine 2018). The impact of satellite imagery on heritage management and protection practice was remarkably positive, and international organizations, practitioners and heritage bodies nowadays regard satellite-based assessment as a source of objective information allowing a conservative estimate of the condition on site.

If satellite remote sensing is now among the research methods usually employed to identify looting, it also appears to be so in the perception of the general (non-expert) public, that has been overflowed by broadcast and social media information on how satellites (particularly, optical images) contributed to assess damage in areas of warfare. A clear example was the media attention that Palmyra gathered when the first satellite image showing the destruction of the Temple of Bel was released (BBC 2015). Interestingly, not only "archaeological looting" has become an entry in the Wikipedia free encyclopaedia **[fig. 1a]**, but also within its description a paragraph is dedicated to "Detecting Looted Sites by Satellite" **[fig. 1b]**.

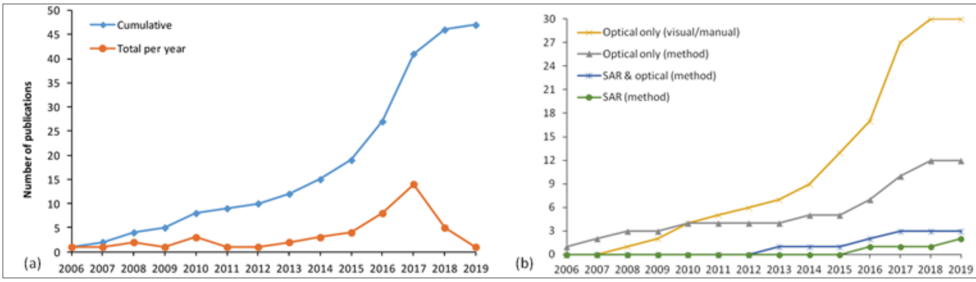


Figure 2 (a) Peer-reviewed publications indexed in Scopus as of mid-2019 where satellite images were used to detect looting at specific archaeological sites and/or image processing methods aimed to detect looting were presented; and (b) their distribution based on the type of images (either optical or synthetic aperture radar, SAR) and the mapping approach (visual/manual, or assisted by an image processing-based method). Modified from Tapete and Cigna (2019b) under the Creative Commons Attribution License

2 State of the Art and User Uptake

Strong evidence of the advancements in this field of research and practice, as well as of how users have increasingly become acquainted with satellite technologies, is retrieved through a bibliographic review of the peer-reviewed publications that were indexed in Scopus during the last 15 years (as of mid-2019) and focused on either the use of satellite imagery for looting assessment at specific archaeological sites, or the development of image processing techniques to detect, monitor and quantify looting. The total of 47 papers published since 2006 [fig. 2a] was the outcome of a steady increase until 2013, with 1 to 3 papers per year. However, no immediate correlation was found between the number of papers and key historical events that happened during 2006-18, i.e. the Arab Spring and the start of the Syrian civil war (conventionally beginning on 15 March 2011), in conjunction of which a significant number of incidents of looting were recorded across the Middle East and North Africa region. In this regard, Casana (2015) analysed the frequency of looting in Syria, by distinguishing pre-war (likely encompassing several decades of activity before 2011) from post-war looting (taking place in 2012-15). He found an increase in looting frequency by nearly an order of magnitude in Syrian heritage sites, although war-related looting was similar in proportion to the record of pre-war looting. Whereas, Parcak et al. (2016) evidenced a statistically significant upward trend in site damage and indicated a greater looting frequency in Egypt following the recession in 2008-09, but prior to the Arab Spring.

In light of the evidence brought by these studies, further insights are gathered if the publications produced by remote sensing researchers and archaeologists are analysed. A clear ramp up of the curve started in 2013 [fig. 2a], with 37 publications published since then, and a peak of 14 papers in 2017.

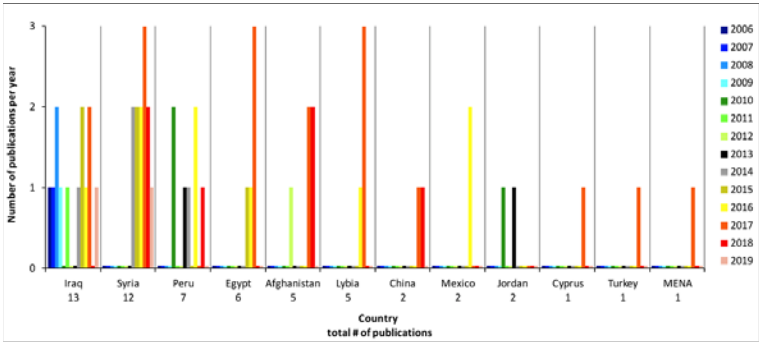


Figure 3 Geographic and temporal distribution of documented looting in the peer-reviewed publications reported in Figure 2. Publication database updated as of mid-2019. Reproduced after Tapete and Cigna (2019b) under the Creative Commons Attribution License

Looking at the geographic distribution where the authors of these papers found evidence of looting using satellite images, Iraq and Syria appear to be the most studied countries with 13 and 12 papers, respectively, followed by Peru (7), Egypt (6), Libya (5) and Afghanistan (5) **[fig. 3]**. These numbers do not provide a ranking of countries most affected by looting. Instead, they indicate which countries were the focus of the literature over the last 5 years.

Papers investigating looting in Iraq and Peru were published more regularly in 2006-19 **[fig. 3]**, while Syria, Afghanistan, Egypt and Libya were covered more unevenly. The constant attention that scholars paid on investigating Peruvian incidents of looting from space demonstrates that looting is a phenomenon that often happens in ordinary times, regardless of political instability that may create favourable conditions for looting to spread. The logistical difficulties of accessing remote regions and managing cultural heritage across vast territories, make satellite remote sensing ideal to produce damage and looting maps as well as incident reports (Tapete, Cigna 2019b).

Accounting for the “spatial focus” and “spatial scale of analysis” at which these studies were conducted, of the 23 publications with a region-specific focus, 7 present inventories of looting incidents covering large landscapes. These papers mostly relied on visualization platforms (Google Earth and Bing Maps) or very high resolution (VHR) satellite imagery. The latter were often sourced through partnerships with government agencies or private foundations (e.g. Hammer et al. 2018). Although studies with site-specific spatial focus still predominate, papers presenting systematic region-specific exercises of looting recording have increased since 2016. This shows how the scope and methodologies of this field of archaeological remote sensing are gradually changing (Cf. Casana, Laugier 2017).

Scholars and practitioners have made efforts to develop methodologies to support the following typical steps of space-based assessment of looting: (1) detection of incidents through the identification of surface features caused by looters; (2) mapping of the detected features to derive spatial information on their distribution and extent; (3) counting of features to quantify the damage extent and/or estimate the rate of looting; (4) if the analysis is repeated in time, multi-temporal monitoring of looting is achieved.

These methodologies essentially differ in how the detection is made, how looting features are mapped, and the scale at which the analysis is conducted. The first major distinction is whether the features are detected and identified visually by the operator, or with the aid of image processing. The literature review highlights that since 2006 visual methods were predominant and mainly applied to VHR optical images **[fig. 2b]**, likely due to the more intuitive identification of looting features in the visible bands, as well as the large volumes of freely accessible data through online visualization platforms (e.g. Google Earth). Since they require image interpretation, these methodologies are frequently questioned for their subjectivity, time-consumption and lack of repeatability and replication (although practitioners are well conscious of the drawbacks and error sources, and implement measures to manage subjectivity, skills gap, lack of standardization and uncertainty; Rayne et al. 2017).

Methods of image processing for looting detection are increasingly being developed **[fig. 2b]**, also in more recent years (e.g. Rayne et al. 2020). This evidence suggests a growing user uptake of these technologies, beyond the expert image analysts. The fact that several papers are co-authored by remote sensing experts and archaeologists suggests that multidisciplinary team working is beneficial to favour such user uptake. A critical review of the image processing-based methods is extensively discussed by Tapete and Cigna (2019b).

3 Synergy Between Optical and Radar Satellite Technologies

Optical and Synthetic Aperture Radar (SAR) data mutually complement each other to detect, document and monitor looting. However, this synergy has not been yet fully exploited by scholars.

So far, most publications used optical images (42 out of 47 papers), in some cases by processing them to extract looting features, in others through visual inspection and manual digitization of looting features. 41 papers used VHR optical data, chiefly sourced from commercial providers, and only 1 paper used Sentinel-2 images at 10 m spatial resolution to assess the spread of looting at site scale (Tapete, Cigna 2018). More recently, an experiment with Landsat 7 ETM+ imagery has been carried out by Agapiou (2020).

Very limited is the exploitation of SAR data (2 and 3 of the analyzed publications used SAR as the sole data source and in combina-

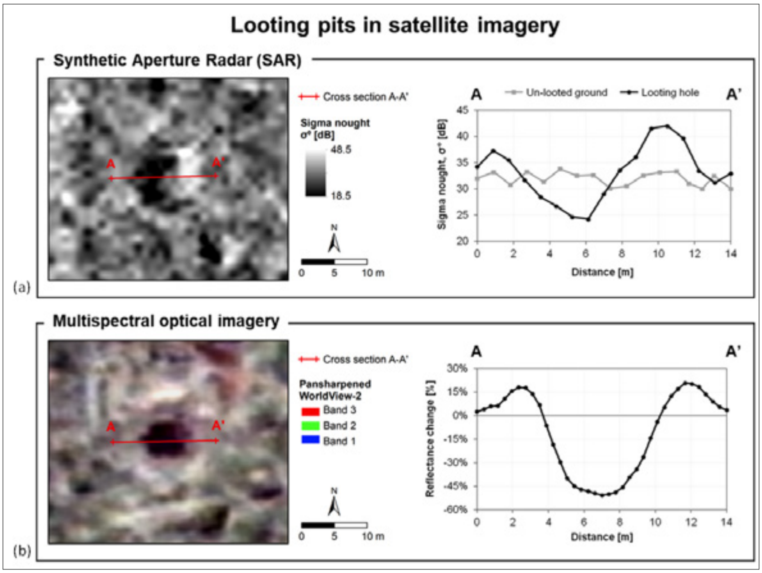


Figure 4 Appearance of looting pit in VHR (a) SAR and (b) multispectral images, and associated normalized radar backscatter sigma nought (σ0) and reflectance change spectral profiles. (a) COSMO-SkyMed® Products ©ASI – Italian Space Agency – 2018-19. All Rights Reserved. (b) WorldView-2 product © 2018 DigitalGlobe, Inc. Distributed by e-GEOS S.p.A. Modified from Tapete and Cigna (2019b) under the Creative Commons Attribution License

tion with optical images, respectively). Main reasons for this are as follows. SAR acquisition modes that can offer the adequate spatial and temporal resolution were released relatively recently (e.g. Tapete et al. 2016). In other cases, even if SAR imagery was available for a long time via dedicated announcements of opportunities by the space agencies (e.g. Italian Space Agency, German Aerospace Center, European Space Agency), only remote sensing experts exploited these data, while most of the heritage community was not aware of their usefulness for looting assessment (Tapete, Cigna 2019a). This is the case of the Spotlight mode data provided since 2007 by the TerraSAR-X mission (i.e. HR Spotlight at 1 m resolution, and Spotlight at 2 m) and the COSMO-SkyMed constellation (i.e. Enhanced Spotlight at 1 m). Another aspect that should not be forgotten is that there is still an important skills gap in SAR data handling across the broader archaeological (remote sensing) community. This limitation contributes to the common misperception that SAR does not have adequate resolution for archaeological applications, is difficult to process and interpret, and therefore is not useful (Tapete, Cigna 2017).

Figure 4 provides an example of a looting hole as imaged by the COSMO-SkyMed SAR constellation in Enhanced Spotlight mode with 1 m ground resolution and 41° incidence angle, and a commercial WorldView-2 image pansharpened with Gram-Schmidt algorithm

(R: Band 3 – red; G: Band 2 – green; B: Band 1 – blue). In the SAR image, the looting pit can be recognized thanks to the geometric distortions that are caused by its morphology and its illumination by the active satellite sensor. Compared to un-looted ground, the radar backscattering profile of the looting hole is characterized by an evident drop due to the radar shadow component of the looting mark, followed by a pronounced increase due to layover **[fig. 4a]**. In the spectral profile of the same looting pit extracted from the WorldView-2 image **[fig. 4b]**, a marked decrease of surface reflectance is found across the extent of the pit compared to the un-looted ground nearby.

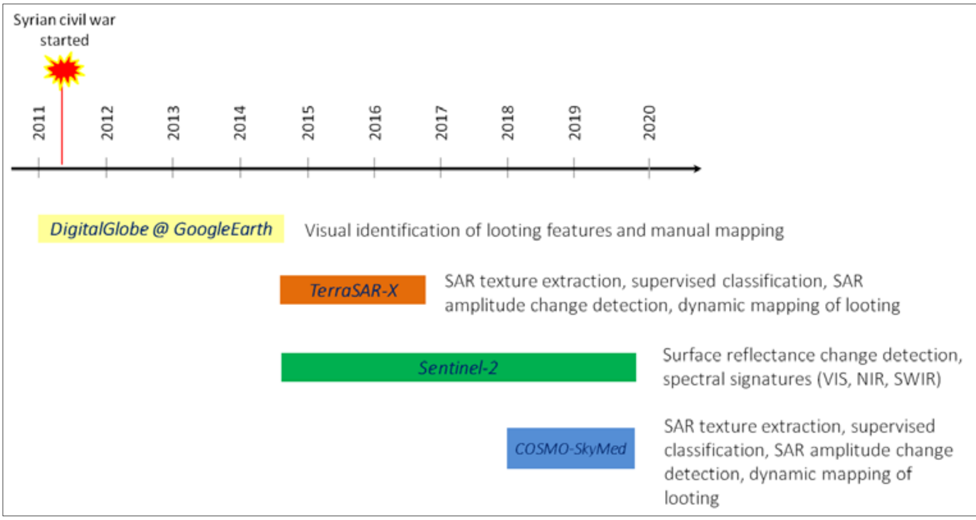
4 Multi-temporal and Multi-sensor Monitoring at Apamea, Syria

Formerly included in the Tentative List of UNESCO in 1999 owing to the richness of its monuments and the high archaeological potential, the site of Apamea has been looted since the start of the Syrian civil war, with the first shocking evidence of damage provided through DigitalGlobe VHR imagery (Casana, Panahipour 2014; Lawler 2014), accessible through Google Earth.

Figure 5 shows the multi-temporal and multi-sensor satellite monitoring that has been carried out since 2013 to track the spread of looting across Apamea in 2011-20, according to the synergistic approach described above. The following looting detection methods have been implemented and combined: visual identification of looting features and manual mapping (Tapete et al. 2016), SAR texture extraction, supervised classification, SAR amplitude change detection, dynamic mapping of looting (Tapete et al. 2016; Tapete, Cigna 2019a, 2019b), surface reflectance change detection, spectral signatures and indices (Tapete, Cigna 2018, 2019b).

Based on Google Earth we could infer that, as of April 2012, 0.93 km^2 (i.e. ~38%) of the archaeological site was looted. Looting devastated ~75% of the excavated sectors plus ~12% of the unexcavated areas. IKONOS satellite data acquired in September 2012 showed that looting holes increasingly started to appear in the private-owned land west of the modern road, from a few clusters covering 0.015 km^2 in September 2012 to 0.105 km^2 in March 2014 **[fig. 6]**.

In agreement with the above estimates, the TerraSAR-X Staring Spotlight data acquired in October 2014 with an unprecedented azimuth resolution of 0.24 m showed that ~45% of the site was looted. Since then, owing to a regular sampling of one image every two months, new looting marks could be observed north of the main Roman *decumani* in 2014-15, and looting rates could be estimated in the order of 780 new looting marks/month in April-June 2015 (Tapete et al. 2016).



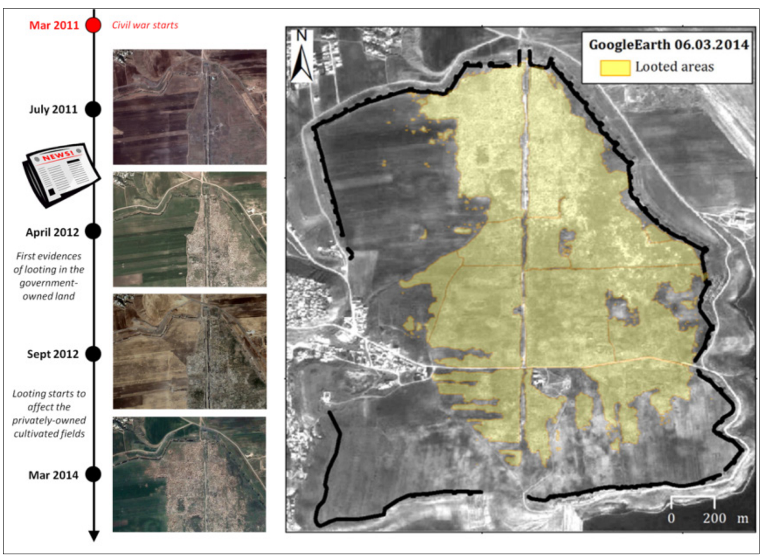
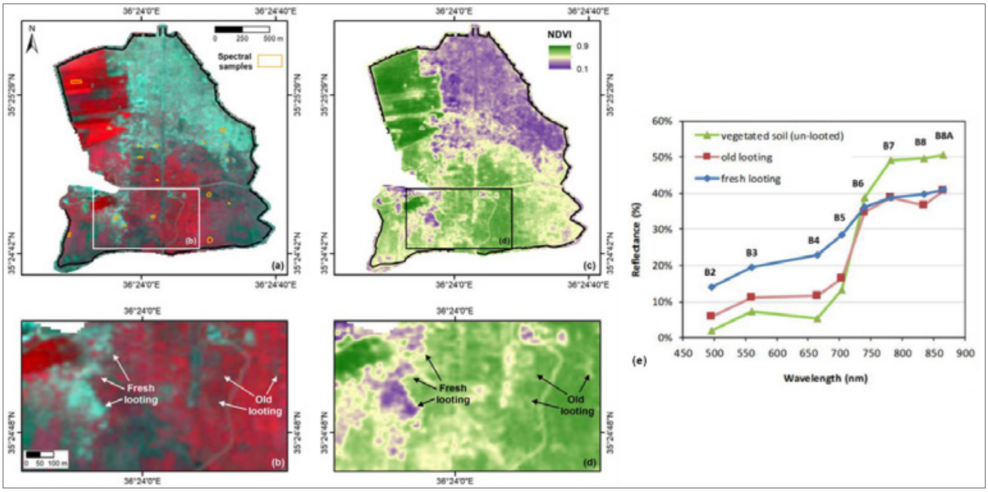


Figure 5 Multi-temporal and multi-sensor satellite monitoring of looting at Apamea (Syria), with indication of the timeline, satellite data and looting detection methods

Figure 6 Multi-temporal monitoring of looting in Apamea in 2011-14 based on Google Earth imagery, through visual identification of looting features and manual mapping. Modified from Tapete et al. (2016) under a Creative Commons license



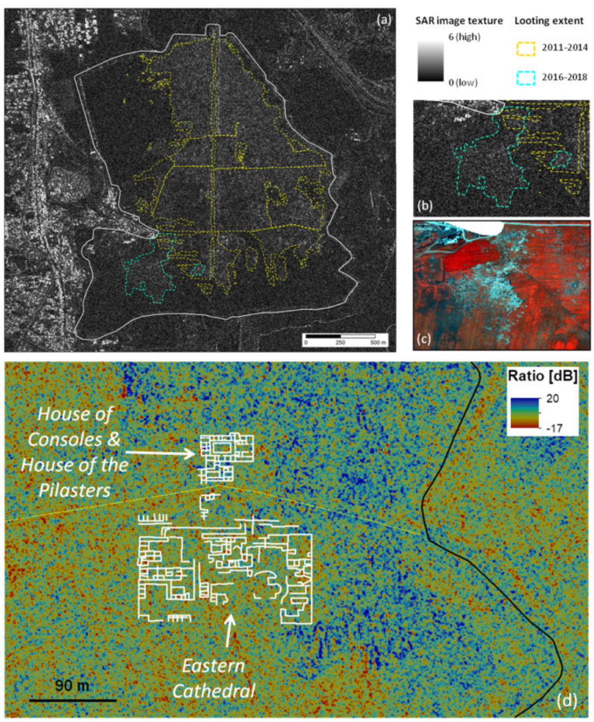


Figure 7 Archaeological looting at Apamea captured with 10 m Sentinel-2 image collected on 21 April 2017 and displayed as: (a,b) false-colored infrared (R: Band 8 – NIR; G: Band 4 – red; B: Band 3 – green) and (c,d) Normalized Difference Vegetation Index (NDVI). (e) Spectral profiles of surface reflectance in VIS and NIR bands. Contains modified Copernicus Sentinel-2 data 2017. Modified from Tapete and Cigna (2019b) under the Creative Commons Attribution License

Figure 8 (a) Texture map of Apamea from a COSMO-SkyMed Spotlight image acquired on 16 July 2018, with indication of areas looted in 2011-14 and 2016-18. The zoomed view in (b) shows a looting cluster south-east of the Roman theatre and (c) the matching false-coloured WorldView-2 product acquired on 03 April 2017 (© 2018 DigitalGlobe, Inc. Distributed by e-GEOS S.p.A.). (d) SAR amplitude change detection map from COSMO-SkyMed scenes acquired in July 2018 and March 2019 shows new looting close to the Houses of Consoles and of Pilasters and the Eastern Cathedral (COSMO-SkyMed® Products ©ASI – Italian Space Agency – 2018-19. All Rights Reserved)

By screening the cloud-free archive of Sentinel-2 from August 2015 to December 2017 to search for any textural and/or surface reflectance changes within the site walls, new looting was clearly detected since February 2016 south-east of the theatre, west of the *Cardo Maximus* and the *Agora*, and in the eastern portion of the archaeological site, along the second main *Decumanus*. Further episodes of looting were also found in 2017. The observed remarkable increase in surface reflectance is compatible with new looting holes being dug and the associated brighter terrain being exposed by the excavations (Tapete, Cigna 2018).

In vegetated sites, this process can be captured and spatially mapped very well through false colour composites **[figs. 7a-b]** and spectral indices such the Normalized Difference Vegetation Index (NDVI) **[figs. 7c-d]**. The latter allows the identification of looting as a "non-green negative mask", wherein some of the older looting clusters appear more faint than the most recent incidents, as also highlighted by the spectral profiles in the visible (VIS) to Near-Infrared (NIR) bands **[fig. 7e]**.

By comparing the previous results with the SAR texture map from a COSMO-SkyMed Spotlight image acquired on 16 July 2018 **[fig. 8a]**, it was found that new looting occurred south-east of the Roman theatre **[fig. 8b]**. The looting cluster started to appear in April 2016 and further expanded until April–May 2017, reaching the extent that was recorded by COSMO-SkyMed. The delineation based on SAR texture is as precise as the looting cluster footprint extracted based on the false-coloured infrared WorldView-2 image at 30 cm spatial resolution **[fig. 8c]**. Furthermore, the SAR change detection map confirmed that new and repeated looting occurred in 2018-19 along the second main *Decumanus* **[fig. 8d]**.

5 Limitations and Future Perspectives

An obvious limitation common to all satellite-based looting assessment methods is the lack of visibility of the looting features. Looting in obscured areas, covered by accumulated sediment, within structures and buildings, or dug as tunnels and holes along slopes, are unlikely to be visible in satellite images. So, not all forms of looting can be recognized using satellite data. Moreover, confusing looting with natural features has been repeatedly reported in the literature as a common cause of misidentification.

Satellite-based assessment of looting has to be carried out in a critical way. Regardless whether such assessment is made by visual identification and manual mapping or through the aid of image processing-based methods, it does nevertheless require, upstream, parameter settings informed by operator's expert knowledge of looting features (and, more generally, of local archaeological specifics) and, downstream, a certain amount of interpretation to use the outputs from the image processing.

Spatial and temporal resolutions of satellite data are critical factors to achieve accurate and granular quantification of damage. However, the spectrum of observation solutions currently provided by past and ongoing satellite missions can be effectively exploited if a multi-temporal and multi-sensor synergistic approach is implemented.

While further efforts are encouraged to widen the user community and their uptake of these technologies, particularly in developing countries and those most affected by looting, there is no doubt that in future more has to be done on several aspects (Tapete, Cigna 2019b). First, by testing the value of automation and machine learning to speed up the detection and mapping steps, while ensuring at least the same level of accuracy. Second, by promoting the sharing of techniques and methods through better networking and collaboration between the different groups working on image processing chain development for space-based looting assessment, in an effort to move towards the definition of protocols and best practices.

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