The Utility of Publicly-Available Satellite Imagery for Investigating Looting of Archaeological Sites in Jordan

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International response to the problem of looting of archaeological sites has been hampered by the difficulty of quantifying the damage done. The scarcity of reliable information negatively impacts professional and public policy making, rendering consensus about the scale of the problem and the effectiveness of policy responses difficult to achieve. We report here on the use of publicly-available satellite imagery for quantifying the damage caused by looting of archaeological sites in Jordan. The ease of use and affordability of imagery such as that provided by Google Earth make the identification, quantification, and monitoring of archaeological site looting possible at a level previously unimagined. Our findings about looting at archaeological sites in Jordan shed light on the potential for a broader application of the method.

Introduction

The market-driven looting of archaeological sites is an internationally recognized problem, though internationally agreed solutions remain elusive. One reason that there has not been a coherent response is that it is difficult to obtain reliable quantitative information "on-the-ground" about either the extent and intensity of looting or the damage being caused. Most relevant data have been collected through archaeological field surveys of both sites and regions, though published surveys of looting damage are few in number and lack diachronic depth (see Brodie and Renfrew 2005: 345–347 for an overview). The paucity of information about the scale of archaeological site looting negatively impacts professional and public policy making for at least two reasons. First, it makes possible claims that the seriousness of the problem is being exaggerated: that most artifacts reaching the market are either "chance finds" (objects discovered through building or agricultural activities), or are from "old collections," and, therefore, strong responses are unnecessary. Second, it is difficult to monitor the effectiveness of any ameliorating policies.

Quantitative information can be obtained from high-resolution aerial and/or satellite imagery, which offers a means of identifying and assessing site damage without time-consuming and expensive site visits. In practice, however, the cost of obtaining suitable images was generally prohibitive for regional-scale projects until recently. The publicly-available imagery from Google Earth might make it possible to sidestep the obstacle of cost, though problems of coverage, appropriate resolution, and surface visibility remain (Beck 2006; Scollar and Palmer 2008; Ur 2006). In this paper, we report on exploratory use of Google Earth imagery for the investigation of site looting in Jordan, paralleling suggestions by Parcak (2009) and Kennedy and Bewley (2009) that Google Earth is a tool well-suited to the task.

CORONA, SPOT, and QuickBird are now available from the United States Geological Survey (U.S.G.S.) National Imagery and Mapping Agency and the Digital Globe Corporation. Approximate dates of these images are the 1960s, 1990s, and 2000s, respectively; resolutions vary from 0.6–2.4 m per pixel (QuickBird) to 0.8–20 m per pixel (SPOT) and costs range from the freely available selection of QuickBird imagery accessible via Google Earth through the \$30 per image CORONA imagery available through the U.S.G.S., to approximately \$250 per 25 sq km (the minimum area for an order) for commercially available QuickBird or IKONOS imagery (for archived imagery; tasked imagery comes at significant added cost). These costs are manageable for single sites but impractical at the regional or national level; 60 cm per pixel QuickBird imagery for the country of Jordan (nearly 90,000 sq km) would cost \$0.9–2.5 million, depending on availability (estimates based on Parcak 2009: 42, table 3.1).

Here, we demonstrate that publicly-available and easy-to-use satellite imagery can serve as an effective tool for documenting and quantifying damage to archaeological sites from intensive looting. The

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method we describe here enables us to offer the first quantified estimates of looting damage in Jordan, as well as assessments of the patterning in selection of sites for looting.

Background

The use of remote sensing in archaeology has a long history (Parcak 2009). Beginning with the early use of aerial photography for site identification in the 1920s and 1930s (e.g., Rees 1929, Shippee 1932) and increased incorporation of satellite remote sensing data in the recent years (e.g., Altaweel 2005; Fowler 2002; Parcak 2007; Saturno et al. 2007; Ur 2003; Wilkinson et al. 2006), remote sensing data have become an important prospection tool.

The potential of satellite imagery as a tool for assessing looting and destruction of archaeological sites has been much less explored, but is amply illustrated by Elizabeth Stone's work in Iraq, which has documented in painful detail the explosion of looting that accompanied war and the collapse of civil authority in that country (Stone 2008a, 2008b). Using Digital Globe imagery purchased for the purpose, Stone documented both spatial and temporal patterns of looting, providing a distressing record of the increased destruction associated with the invasion of Iraq in 2003. She was able to characterize the areal extent of the looting, noting that it comprised (as of 2006) "an area many times greater than all archaeological investigations ever conducted in southern Iraq" (Stone 2008b: 137). In addition, Stone highlighted the selective looting of sites for marketable materials, and was able to track changes in looting behavior over time for some sites.

Similar methodology has been employed in two other projects in Iraq, though with slightly different data sources (Hritz 2008; Van Ess et al. 2006), and in one project in Egypt (Parcak 2007). Hritz hypothesized that the risk of looting and site destruction is likely to be a function of the proximity of sites to modern settlements and infrastructure, as well as their periods of occupation, which would cause targeting of sites for marketable materials (Hritz 2008: 4). Preliminary results of her analyses of satellite imagery, however, show that, "Sites of all periods are being looted and their proximity to modern villages is varied" (Hritz 2008: 7). Margarete Van Ess and her colleagues applied a similar method in utilizing IKONOS imagery to map both archaeological features and looting damage at Uruk (Van Ess et al. 2006).

We have looked at remote sensing methods with two key questions in mind. First, is it possible to use exclusively free or low-cost imagery to identify and interrogate evidence of looting and site destruction, making the type of monitoring pioneered by Stone and Hritz possible without substantial monetary investment? Specifically, we examined the freely available and increasingly popular program Google Earth, which now makes a variety of types of satellite imagery, including sub-meter per pixel visual spectrum imagery from the QuickBird satellite owned by the Digital Globe corporation (Parcak 2009: 43–51), publicly available at no cost. Second, how can information obtained through remote sensing methods be combined with other types of data to generate quantitative studies of archaeological site looting?

As a case study, we examined the country of Jordan (FIG. 1). The long history and continued existence of looting in Jordan is suggested by a variety of sources (Bisheh 2001; McCreery 1996; Papadopoulos et al. 2001; Politis 1994, 2002; Rose and Burke 2004), though the nature and scale of its impact on the archaeological record have not been systematically investigated. Moreover, with a couple of notable exceptions, little effort has been made to investigate the social, political, or historical contexts of looting, or its economic importance (if any) to local communities. Thus, our starting premise was that the more established methods of archaeological survey, particularly pedestrian surface survey and aerial photography, have failed to record or quantify evidence of archaeological site looting in a systematic fashion. We asked whether low-cost, publicly-available satellite imagery can now remedy this methodological shortfall.

Pedestrian surface survey is a well-established technique of archaeological prospection and landscape evaluation. Surveys are ideally suited to identifying, characterizing, and quantifying looted sites, as has been demonstrated in Turkey (Roosevelt and Luke 2006a, 2006b). Unfortunately, in Jordan, the potential of such surveys to investigate the extent and organization of archaeological site looting has not been realized. As an example, it is instructive to consider the experience of the Wadi Faynan Landscape Survey, conducted between 1996 and 2000, and considered to be a "flagship" project of the British Institute at Amman for Archaeology and History (BIAAH) (Palmer et al. 2007: 57). At the time of the project's inception, the BIAAH was already engaged in rescue excavation of a heavily looted Late Roman to Byzantine cemetery located in what was to become the survey area (Site WF3: the South Cemetery) (Barker et al. 2007: 8). Tomb robbing at the South Cemetery had been reported as early as 1934, again in 1986, and by 1996 more than 700 graves, estimated to comprise 40% of the total number, had been badly damaged (Findlater et al. 1998: 71–72). Despite this visible economic exploitation of an archaeological site, and the survey directors' awareness that "the landscape history of Faynan had to include its contemporary inhabitants" (Barker et al. 2007: 17), very little was done during the survey to investigate the problem. The site

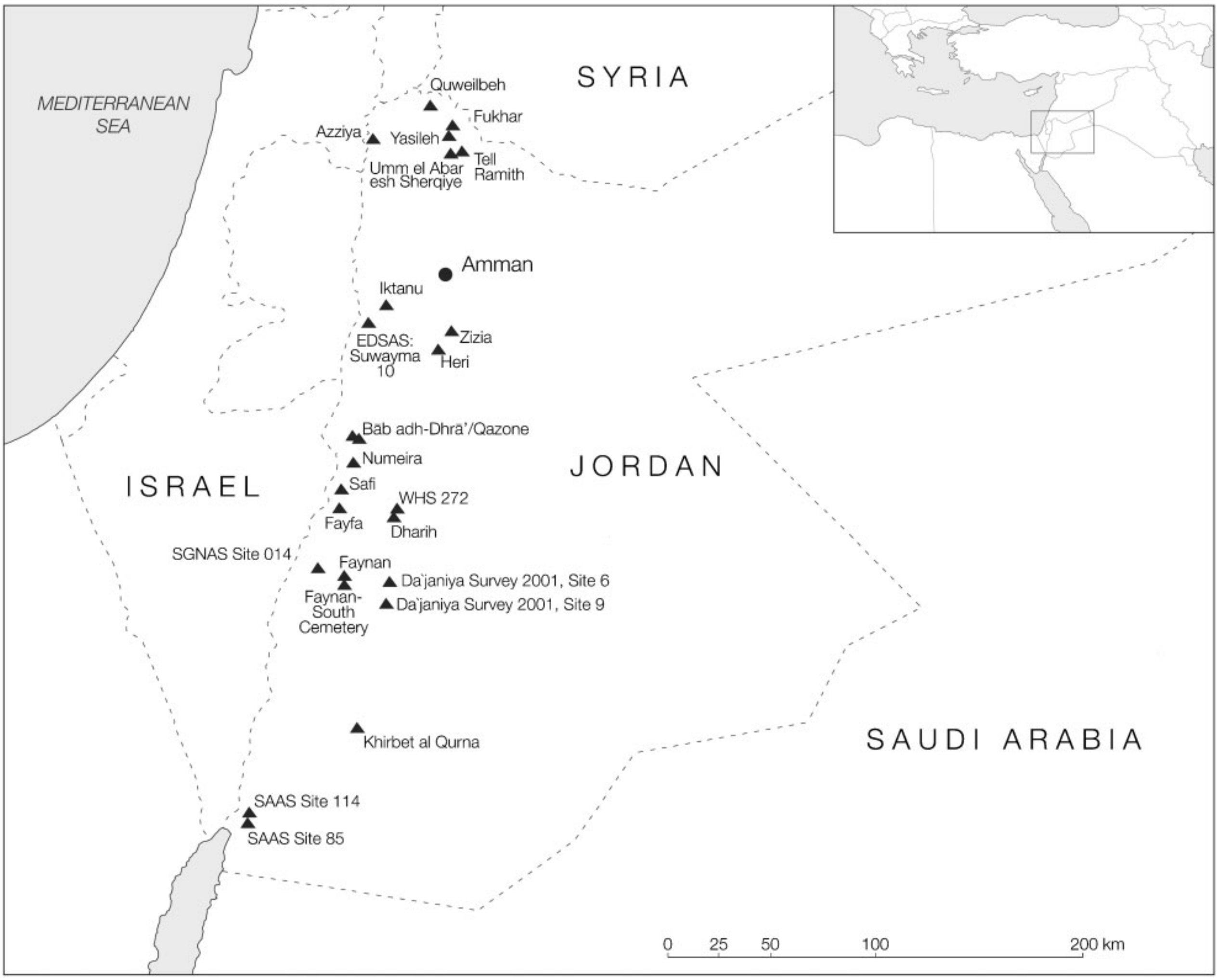

Figure 1 Sites evaluated for looting damage.

gazetteer records at least 52 sites composed of one or more looted graves (Mattingly et al. 2007). Although the survey identified a range of activities of the local tribespeople, tomb robbing was not one of them (Palmer et al. 2007: 38). There was no attempt to uncover the history and organization of archaeological site looting, nor was there any consideration of its impact on the local Wadi Faynan economy, which might have been significant if it resembled the situation in north Jordan (Rose and Burke 2004). What is most alarming, however, is the suggestion made in the final report that tomb robbing in the area only became a problem after archaeological field projects had acted to change local perceptions of archaeological heritage (Palmer et al. 2007: 52). The ethical problems raised by that suggestion remained unexplored.

The Wadi Faynan survey was not unusual in its reluctance to engage with the interpretative and ethical problems raised by archaeological site looting, and researchers might point to finite time and resources and other investigative priorities. The Wadi Faynan survey illustrates what can be described as an archaeological blindspot. Instead of being an object of archaeological research (human action on the landscape), looting is considered to be an obstruction to research (a post-depositional process). Pedestrian archaeological survey, which in principle should be the methodology best suited to investigating archaeological looting "on the ground," has in practice done very little to improve our understanding of the problem.

A similar criticism can be applied to the use of aerial photography, though for different reasons. The archaeology of Jordan has perhaps been photographed from the air more than that of any other country, and yet, as with surface survey, the accumulated photography has done little to illuminate the problem of archaeological site looting. For aerial photography, the reasons for that failure seem to arise more out of logistics and technical limitations than out of self-imposed disciplinary constraints. Aerial photography focuses on archaeological features that are visible from the air and are the remains of what were originally surface structures (Kennedy and Bewley 2004: 53). Most looted sites are cemeteries, and therefore they are usually not visible from the air until after they have been looted. Furthermore, recent aerial survey in Jordan has endeavored to produce good quality, high-resolution documentation of sites already known from older small-scale photographs taken in the 1940s and 1950s

(Kennedy and Bewley 2009). In this context of "active" aerial archaeology (Kennedy 1998: 91), it is an expensive and thus poor use of flying time to engage in reconnaissance for previously unknown looted cemeteries. Although Kennedy and Bewley have demonstrated the utility of a time series of aerial photographs for documenting damage caused to archaeological sites by agricultural or other land alteration and emphasized the merit of aerial photography more generally in heritage management (Kennedy and Bewley 2009: 75, figs. 7, 8), they have also, inadvertently perhaps, demonstrated the limitation of the method, where evidence of illicit digging intrudes on the margin of a photograph as an incidental rather than a central feature (Kennedy and Bewley 2009: 77, fig. 6). Although satellite imagery currently does not offer comparable resolution to good quality aerial photographs, it does address a methodological shortfall of aerial photography in that it allows inspection of areas of interest without the time, expense, and logistical difficulty of arranging specific flights. Google Earth imagery has been specifically recommended for this purpose (Kennedy and Bewley 2009: 80).

Another reason for choosing Jordan as a case study was that at the time of the present project's inception, a significant catalog of archaeological sites existed for the country, making their location on satellite imagery efficient and reliable, and the identification of sites by time period feasible. Specifically, the Jordan Antiquities Database and Information System (JADIS) Project of the Jordanian Antiquities Service (Palumbo 1993, http://www.nis.gov.jo/pls/anti/sitetype) and the Digital Archaeological Atlas of the Holy Land (DAAHL) maintained by Geo-Archaeological Information Applications Lab of the School of Human Evolution and Social Change at Arizona State University (http://gaialab.asu.edu/DAAHL/AboutAtlas.php) provided site locations and periods of occupation. These two projects (whose websites are no longer available), along with the Mediterranean Archaeology GIS (MAGIS) database of archaeological survey projects in the Mediterranean maintained by DePauw University (Foss and Schindler 2008), served as excellent guides to the relevant publications where further information was available. Future projects may be facilitated by the Middle Eastern Geodatabase for Antiquities, Jordan (MEGA-J) currently under development by the Getty Conservation Institute and the Jordanian Department of Antiquities (Getty Conservation Institute 2008).

Technical Considerations

Assessing site destruction and looting damage through use of aerial and/or satellite imagery may result in two basic kinds of studies: "longitudinal," in which a time-series of images are compared one against another to track patterns of looting behavior over the time period spanned by the available imagery, or "snapshot," in which a single image may be used to quantify the extent of looting at the point in time when the image was collected. Either type of study may also include comparison amongst a variety of different sites or regions. To minimize contrasts in visibility resulting from imagery of varying quality, such comparisons should ideally be carried out utilizing the same imagery. Of course, in the case of imagery from past decades that is often not possible, and one must use whatever is available.

Longitudinal studies offer the possibility of assessing historical trends, producing data critical for analyzing the factors influencing looting (e.g., infrastructure changes, market dynamics, regulatory interventions, etc.). Tracking landscape change over time in a single locality, however, requires the acquisition, georeferencing (registration in map coordinates), and analysis of multiple images, implying significant time and expense, and is of course dependent on the existence of historical imagery. The recently released Version 5.0 of Google Earth (postdating the research reported here) incorporates imagery which Google Earth has archived since 2003, making short-term longitudinal studies possible using exclusively Google Earth imagery, where multiple images of sufficient resolution are available. Snapshot studies do not offer the same historical detail, but by definitively describing the extent of looting damage at a given point in time, they provide a valuable baseline measurement against which other images (either historical or yet to be collected) may later be compared. We focus here on the latter kind of study, with a single example of the use of historical aerial photographs included for comparison.

Assessing the incidence and areal extent of looting through use of aerial or satellite imagery is dependent on identifying evidence of looting activity on the landscape, which itself is dependent on the quality of the available imagery and on a recognizable visual signature of illicit excavation. Image quality, in this context, has two primary aspects: coverage and resolution. The utility of remotely-sensed imagery is a function of the existence of unobscured (e.g., by cloud cover) images of the exact region of study and of the ratio of ground area to image pixel, which determines the scale of identifiable and even visible features (commonly expressed in meters/pixel).

A further, but less-discussed aspect of remotely-sensed imagery is also of interest to archaeologists: cost. Previous satellite investigations of looting damage required significant funding with which to obtain high-resolution imagery and expertise in remote sensing and/or GIS software (Hritz 2008; Stone 2008a, 2008b; Van Ess et al. 2006). We managed cost by using Google Earth Pro and tested whether the coverage and resolution of Google Earth images were adequate for research purposes. In August 2008, the annual cost of a license for Google Earth Pro was $400; academics may apply for free access (http://earth.google.com/outreach/program_details.html). The imagery used in Google Earth Pro is the same as that used in the free version of Google Earth, but GE Pro allows the export of images at high resolution. Given the need in the present project of working with ArcGIS as well as Google Earth, the Pro version was necessary. For simple identification of looted areas, the free version of Google Earth would serve perfectly well. Ur (2006), Beck (2006), Scollar and Palmer (2008), and Parcak (2009: 43–51) have all discussed the utility of Google Earth for making remote sensing imagery more affordable and accessible to archaeologists. The wide availability and user-friendly interface of Google Earth suggest that it may be possible to engage a wider range of individuals and agencies in the documentation of looting damage, but only if it is possible to demonstrate the utility of Google Earth specifically (as opposed to satellite remote sensing generally) for this purpose and establish a viable methodology.

Using satellite imagery in this way is not without its own problems. Ur (2006) and Parcak (2009: 224) highlighted the potential hazard of making site locations known to potential looters. We do not consider this to be a significant danger for our own research, as we are concerned with identifying and quantifying sites that have already been looted, or that are in the process of being looted. Presumably, in such circumstances, the looters have nothing to learn from published images of their work. While Ur and Parcak have valid concerns, we examined whether Google Earth could serve to document, quantify, and even monitor looting.

Finally, the method is further constrained by the quantity and quality of data available on locations and descriptions of archaeological sites in the region of interest. In our test case, JADIS and DAAHL provided information on sites in Jordan, but also limited our research by their imperfect coverage. These databases were remarkable, publicly-available resources, but the level of detail of coverage varied (unsurprising given that they were based on survey data from a variety of sources), and coverage was unevenly distributed throughout the country. Variation in coverage could be visually estimated by noting the substantial unevenness in site density, and more precisely assessed using data from the MAGIS Project (Foss and Schindler 2008), which provided an excellent (if not totally comprehensive) source for review of surveyed areas. Kennedy and Bewley (2004: 53) estimate that detailed examination of vertical air photographs of western Jordan in the 1990s identified approximately three times as many sites as had been documented in JADIS.

Thus, the variable coverage of the site database limited the area that could be searched for looting damage. This was not a serious limitation, as the area in any case study is also limited by the impracticality of visually inspecting every square kilometer. It is likely that the biases in archaeological knowledge seen in the distribution of known sites and their dates of occupation parallel those in looting damage. In other words, archaeologists and looters are both likely to discover and exploit sites that stand out because of their relative ease of accessibility and identification. It seems probable, therefore, that the number of major looted sites completely absent from the available archaeological database should be small or nonexistent, at least in the type of well-surveyed area appropriate for a study like this one. In unsurveyed areas, it is fairly common for newly identified sites to be discovered by looters.

Methodology

Two methods of prospecting for looted areas were employed, both utilizing the DAAHL database. First, the DAAHL database was filtered for cemetery sites—deemed the most likely targets for looters because of the availability of intact ceramics and other saleable grave goods—and the resulting collection of 406 sites was downloaded as a .kml file (a geographic location and associated display information in keyhole markup language) that could be imported directly into Google Earth. The areas immediately surrounding each of these sites were inspected for signs of obvious and extensive looting, visible as pitting on aerial and/or satellite images (highly contrasting intermingled dark and light pixels, distinct from the basically monochromatic, unmodified landscape) (FIG. 2). This was possible because Google Earth incorporates sub-meter/pixel QuickBird imagery for much of Jordan. The correspondence between pitting identified on images and looting on the ground was established from areas previously documented as badly damaged by looting (Bāb adh-Dhrā'and Khirbat Qazone, as described below, and also Safi; Papadopoulos et al. 2001; Politis 1994, 1998a, 1998b, 1999, 2002; Politis et al. 2005; Politis et al. 2007). Where looting was identified, the location was marked with a rough polygon and noted for later evaluation. In total, 18 sites with indications of looting were identified using this method. The relatively low number of looted cemeteries identified should not, however, be taken as an indication of the scarcity of looting. JADIS includes reports of few isolated burials, and only relatively extensive looting is identifiable on remote sensing imagery.

First, the entire DAAHL database of sites for Jordan (>12,500 sites) was downloaded as a .kml file, and all sites in the vicinity of major roads were

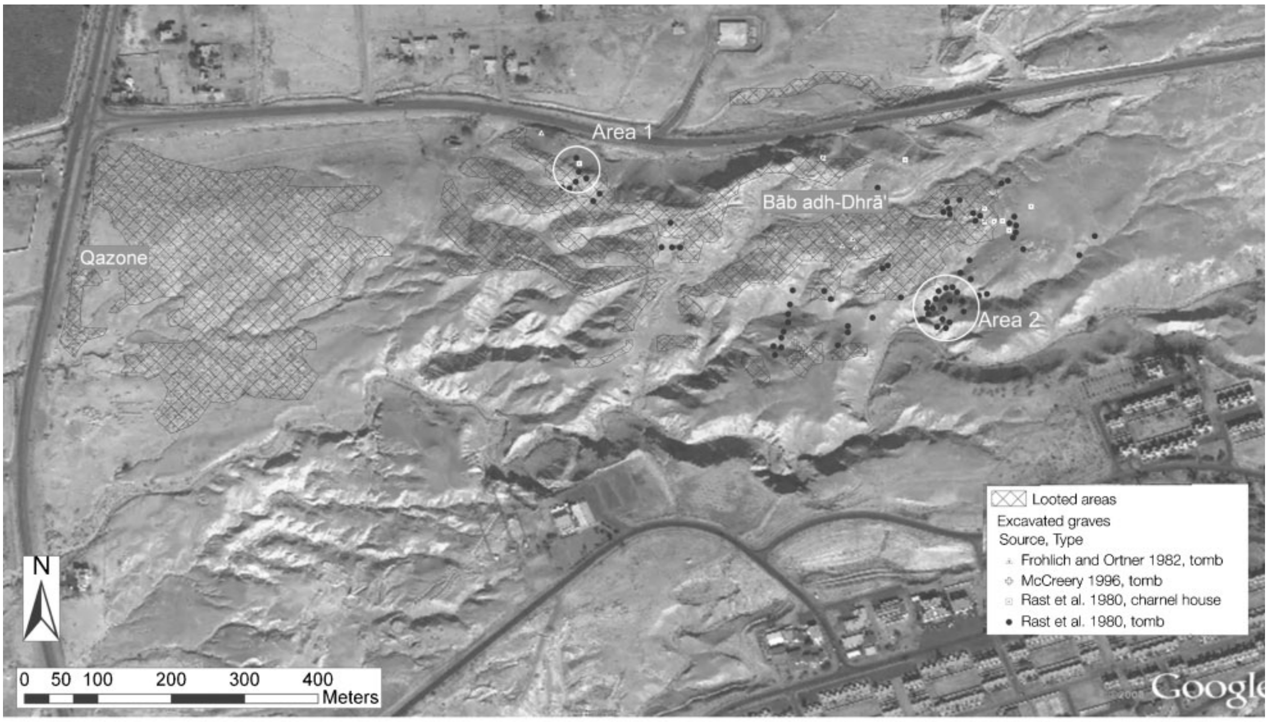

Image downloaded from Google Earth Pro 6 Aug 2008.
Digital Globe Image. Catalog ID 10100100056B6601. 11 Jan 2007.

Figure 2 Google Earth image of Bāb adh-Dhrā' (2007), showing damage from looting and areas excavated.

visually inspected for evidence of looting. Both Stone (2008a, 2008b) and Hritz (2008) suggest that accessibility is a major risk factor for sites in Iraq. Second, the Digital Chart of the World (DCW) vector data (Penn State University Libraries 1992) of Jordan's road network were used to create buffer corridors 2 km wide in ArcGIS 9.2, centered on each of the major roads in Jordan. Mismatch between DCW roads and those visible in Google Earth—the result probably of both dated DCW data and distinct projections—caused some imprecision here; the buffers were not taken as precise corridors but rather as a means of easily identifying sites in the DAAHL database that were relatively close to major roads. Four additional sites were identified using this method, and three others were identified from literature references (see below). In both cases, heavily urbanized areas were largely ignored because of the difficulty of visually identifying looted areas therein. Note that the identification of these sites as looted areas is necessarily made with varying degrees of confidence, depending on image quality and the scale of looting. Ground truthing would be necessary for 100% confidence to be assigned to our identifications. Where possible, published accounts of looted areas (e.g., McCreery 1996; Politis 1998a, 1998b, 2002) have been used to confirm identifications. In sum, approximately 26% of the sites listed in JADIS were visually inspected.

The 25 sites recognized using this combination of methods (FIG. 1) were investigated further. Once looted areas were identified, .jpg images were downloaded from Google Earth Pro at the highest resolution possible (4800 × 3229 pixels), and georeferenced in ArcGIS 9.2 using the procedure outlined by Tripcevich (2008) with minor modifications (placemarks rather than the Latitude/Longitude grid were used for georeferencing purposes). The images exported from Google Earth Pro were adjusted (contrast, brightness, and color balance) to improve visibility of features in Corel Photo-Paint where necessary. The provider, date, and Catalog ID number of the satellite images tiled by Google Earth to create the captured images were identified (accessible in Google Earth by turning on the layer Primary Database→More→DigitalGlobe Coverage) and noted in the metadata (associated information about each file) for each image downloaded and georeferenced.

Areas visually identified as looted were used to create boundary polygons in ArcGIS, focusing on densely pitted terrain. Since image resolution was generally not adequate to allow counting of individual pits and thus direct estimates of pit number and density, we instead approximated total looted area, bounding the visibly disturbed areas (FIG. 2). In several cases, this led to the definition of multiple polygons for a single site. This approach limited the precision of our measurement, but had the advantage of being simple and easily replicable. We adopted it in hopes that it might be widely and easily emulated. In contrast, Van Ess and her colleagues (2006) employed a more sophisticated approach to identifying looted areas, relying on object-based image recognition, but used a method appropriable only by specialists.

The resulting shapefile (geometric vector data in the native ArcGIS file format) was then used to calculate looted area in sq m/site. For each site, the published literature was consulted in order to confirm, if possible, that the features identified were in fact looters' pits and to identify the period(s) to which the looted site was assigned, in order to assess what sorts of artifacts it might yield for the illicit antiquities market.

Spatial context (proximity of sites to populated places and infrastructure) was provided by the DCW vector data (Penn State University Libraries 1992), which was also used to calculate the buffers created for site identification (described above). Attributions of looted sites to time periods were made on the basis of published material on those sites; sources are noted in the "References" column of Table 1.

Assessing the Method

Bāb adh-Dhrā'

The spatially contiguous cemeteries of Bāb adh-Dhrā' and Khirbat Qazone (henceforth Qazone), located on the southeastern plain of the Dead Sea, were used to assess the reliability of the method and to illustrate some of its potential. Both sites are well documented in the archaeological literature, and are registered in both JADIS and DAAHL. Pitting is clearly visible in the Google Earth imagery of the area (FIG. 2) and on the ground (FIG. 3).

The Early Bronze Age (EBA) cemetery of Bāb adh-Dhrā' has been known to archaeologists since the 1920s, and as early as 1924 there was evidence of looting (Albright, 1924:59). The site was first excavated in the 1960s by Paul Lapp (Lapp 1966; Lapp 1975: 104–110; Ortner and Fröhlich 2008; Schaub and Rast 1989). Lapp excavated 53 EBA tombs, spatially clustered in two areas, which he designated Cemetery A in the eastern part of the site and the smaller Cemetery C in the northwestern part (Schaub and Rast 1989: 25). Most of the tombs excavated were EB IA shaft tombs—33 in total (Schaub and Rast 1989: 35–318). Each shaft tomb was composed of one or more burial chambers, dug out radially from the bottom of an axial shaft. Shafts were typically 1.5 m deep, and burial chambers were 2 m in diameter (Ortner and Fröhlich 2008: 2). In total, for the 33 EB IA shaft tombs, 53 burial chambers were excavated, each one containing multiple inhumation burials and associated artifacts (TABLE 2). Evidence of illegal digging was noted for eight tombs (A3, A11, A66, A81, A82, A83, A84, and C3), but only one tomb (A84) seems to have been badly damaged, since a substantial quantity of pottery was recovered from all tombs except A84, in which only three pots were found. The second most frequent tomb type was the EB II-III charnel house. Eight were excavated, with a ninth charnel house dating to EB IB (Schaub and Rast 1989: 319–472).

Excavations at the cemetery resumed in 1975, as part of a larger project aimed at investigating the adjacent settlement of Bāb adh-Dhrā' and its hinterland (Rast and Schaub 1979). Over four seasons (1975, 1977, 1979, and 1981), a further 27 EB IA shaft tombs composed of 63 burial chambers were excavated (Fröhlich and Ortner 1982; Rast and Schaub 1978, 1979; Rast et al. 1980; Schaub 2008). Most of these tombs were located in the area of Cemetery A, though two were located midway between Cemeteries A and C in Area G. One additional tomb was excavated in Cemetery C. Most chambers appeared to be undisturbed by looting, though two had been robbed completely, and several more robbed tombs were noted in Area G (Rast and Schaub 1979: 53). Three additional charnel houses were excavated (Rast and Schaub 1979: 62–66; Rast et al. 1980: 37–39).

In the early 1980s, then, it was still possible to locate many undisturbed tombs at Bāb adh-Dhrā', and though there was evidence of tomb robbing, the cemetery appeared to be reasonably intact. By the mid-1990s, however, the situation had deteriorated. A short rescue excavation conducted there in 1995 investigated 39 previously unrecorded EB IA shaft tombs (clustered in a small area of the cemetery, and composed of 64 chambers), that had been uncovered by illicit digging (McCreery 1996). Of the 44 unsilted chambers investigated, only 20 yielded whole or restorable pots; the remaining 20 chambers had clearly been emptied of their contents.

Thus, tomb robbing is well documented at Bāb adh-Dhrā', and has caused the pitting visible in Google Earth images. The published excavation reports do not contain enough information to permit a quantitative estimate of the number of tombs destroyed, nor can one be made by counting pits on a satellite image (they cannot be individually identified with confidence due to the limitations of image resolution). The fact that the looted area could be calculated from the satellite imagery allowed an estimate to be made of the number of looted tombs by multiplying the total area looted (calculated from the satellite image) by the areal density of tombs (known from the excavation reports). Using excavation reports to calibrate satellite images in this way was not straightforward because of the rarity in reports of precise, georeferenced mapping or explicit description and/or illustration of robbed tombs. The site reports focus instead on intact excavated tombs and map in local coordinates. (e.g., Lapp 1966; Rast and Schaub 1978, 1979). In addition, different projects commonly used different coordinate systems and datum points (Politis et al. 2005). Nevertheless, some extrapolation was possible.

In order to arrive at an estimate of the archaeological damage caused by the looting at Bāb adh-Dhrā', it is necessary to know the following: a=the total area looted (sq m); c=the number of burial chambers per sq m; and p=the mean number of pots per burial chamber. Given these values, it is possible to calculate: $c \times a$=total number of chambers damaged by looting and $c \times a \times p$=total number of pots looted.

The history of excavations at Bāb adh-Dhrā' demonstrates that the incidence of tombs and burial chambers is not constant across the site, nor was the provision of pottery, as follows. The tombs of Cemetery C are on average smaller and were more poorly provisioned than those of Cemetery A (TABLE 2). Thus, it was necessary to calculate two estimates of the damage: a low estimate based on the Cemetery C statistics, and a high estimate based on the Cemetery A statistics. The true figure would lie somewhere in between.

Table 1 Sites identified as looted using Google Earth imagery. Those discarded following ground truthing and not listed are EDSAS Suwayma 10 and SAAS Site 85 and 114. The revised total reflects the discard of those three sites.

Site	*Period*	*Type**	*Area looted (sq m)*	*Date of imagery*	*References*
Azziya	Iron Age, Hellenistic, Roman, Byzantine	II	6747	2004	Glueck 1951
Bāb adh-Dhrā'	Early Bronze Age	I	74,377	2007	Chesson and Schaub 2009; Fröhlich and Ortner 1982; Lapp 1966, 1968; McCreery 1996; Politis 1998a, 1999; Rast and Schaub 1974, 1979; Rast et al. 1980; Schaub 1993; Schaub and Chesson 2009; Schaub and Rast 1984, 1989
Da'janiya Survey 2001 Site 6	Early Roman/Nabatean, Late Roman, Early Byzantine	I	2393	2004	Rucker 2007
Da'janiya Survey 2001 Site 9	Late Roman, Early Byzantine	I	4935	2004	Rucker 2007
Dharih	Late Roman/Nabatean/ Early Christian	II	2522	2005	Lenoble et al. 2001; MacDonald 1988
Fayfa	Early Bronze Age	I	62,170	2004	MacDonald 1992; MacDonald et al. 1987; Rast and Schaub 1974
Faynan	Roman/Byzantine	I	6934	2004	Barker et al. 2007; Mattingly et al. 2007
Faynan - South Cemetery	Late Roman–Early Byzantine	I	9674	2004	Barker et al. 2007; Findlater et al. 1998; Mattingly et al. 2007
Fukhar	multi-period	I	7851	2004	de Vries 1992
Heri	"Moabite"	I	1419	2003	Kennedy and Bewley 2004
Iktanu	Early Bronze Age	II	2661	2006	Kennedy and Bewley 2004
Khirb et al Qurna	Roman/Nabatean	I	3642	2003	Kennedy 2002; Kennedy and Bewley 2009
Numeira	Early Bronze Age	I	13,163	2004	Rast and Schaub 1974
Qazone	Nabatean	I	80,469	2007	Politis 1998a, 1999
Quweilbeh	Late Roman	I	6689	2005	Bisheh 2001; Kennedy and Bewley 2004
Safi	Early Bronze Age	I	19,473	2004	Jones et al. 2000; MacDonald 1992; Papadopoulos et al. 2001; Politis 1994, 1998b, 2002; Politis et al. 2005; Politis et al. 2007; Rast and Schaub 1974; Waheeb 1995
SGNAS Site 014	Chalcolithic/Early Bronze Age	I	4337	2004	MacDonald 1992
Tell Ramith		IV		2004	
Umm el Abar esh Sherquiye		IV		2004	
WHS 272	Nabatean	II	812	2005	MacDonald 1988
Yasileh	Late Roman–Byzantine	I	10,672	2004	Al-Muheisen 1991; Rose and Burke 2004
Zizia		III	19,149	2004	
Original estimate of total looted area:			535,160		
Revised total			**515,351**		

* Type I=looting noted in literature; Type II=looting not noted in literature; Type III=site not in literature, looted; Type IV=possibly looted.

The total area looted (a)

The total area looted (*a*) is estimated from 2007 to be 74,377 sq m (TABLE 1).

The number of burial chambers per sq m (c)

The densest concentration of tombs in Cemetery C comprises six tombs and thus 6.6 chambers (given a mean for Cemetery C of 1.1 chambers per tomb) (TABLE 2) in Area 1 (FIG. 2). Area 1 measures 700 sq m, and therefore $c=6.6 \div 700=0.009$. The densest concentration of tombs in Cemetery A comprises 17 tombs and thus 35.7 chambers (given a mean for Cemetery A of 2.1 chambers per tomb) (TABLE 2) in Area 2 (FIG. 2). Area 2 measures 2250 sq m, and therefore $c=35.7 \div 2250=0.016$.

The mean number of pots per burial chamber (p)

As Table 2 shows, for Cemetery C, $p=14$, and for Cemetery A, $p=23.6$.

Low damage estimate (based on the statistics for Cemetery C)

The calculated total number of burial chambers damaged by looting is $c \times a=0.009 \times 74{,}377=669$. The total number of pots removed is calculated as $p \times 669=14 \times 669=9366$.

High damage estimate (based on the statistics for Cemetery A)

The total number of burial chambers damaged by looting is $c \times a=0.016 \times 74{,}377=1190$ and the total number of pots removed: $p \times 1190=23.6 \times 1190=28{,}084$.

These estimates of the amount of material looted from Bāb adh-Dhrāʾ represent formidable figures, and the high estimate in particular seems suspect. There is no reason to believe that rich Cemetery A type tombs were found across the whole cemetery area. Cemetery C types might have been more widespread than is evident from the excavated areas. There is no guarantee either that all the looting pits penetrated burial chambers, though it seems most likely that pitted areas do represent looted tombs. Looters would not dig extensively in sterile areas, particularly if they were using long probing rods to locate chambers. A mean estimate of 18,725 pots—the average of the two estimates—removed over a period of several years, perhaps a decade or more, might still appear high, but is not contradicted by what is known about the market for such pottery. In 1996, for example, the London dealer Chris Martin, who was selling large quantities of Jordanian EB IA pottery, speculated that there were between 10 and 15 million pots in the ground at Bāb adh-Dhrāʾ (Newnham 1996). Ground truthing—counting looters' pits in a given area, and identifying the type of tomb looted—would be necessary to assess the accuracy of our estimate.

Figure 3 Bāb adh-Dhrāʾ/Qazone in 2004 showing pitting. Photograph by Neil Brodie.

Khirbat Qazone

For the adjacent cemetery of Qazone, more detailed testing of our methods was possible. In 1979, a survey of the lower ground immediately to the west of the Bāb adh-Dhrāʾ cemetery reported Roman, Byzantine, and Ummayad sherds on the ground surface, but nothing more (Rast et al. 1980: 40). In 1994, construction to widen the road uncovered the previously unknown cemetery of Qazone. It was rapidly looted and rescue excavations conducted there in 1996–1997 counted more than 3500 robbed shaft graves, dating to the Nabataean period (Politis 1998a). This count—though the exact methodology through which it was produced remains unspecified—offered an opportunity to assess the accuracy of

Table 2 EB IA tomb and pottery statistics. Statistics for 1965–1967 (Schaub and Rast 1989: 184, table 5, 203, table 8) exclude atypical tomb A1 and looted tomb A84. Statistics for 1975–1981 (Schaub 2008: 28–29, tables 4.1–4.3) exclude looted tomb A112.

Excavation	*Number of tombs*	*Number of chambers*	*Mean number of chambers per tomb*	*Total pots recovered*	*Mean number of pots per chamber*
1965–1967 Cemetery A	26	46	1.8	1128	24.5
1965–1967 Cemetery C	6	6	1.0	50	8.3
1975–1981 Cemetery A/G	24	59	2.5	1351	22.9
1975–1981 Cemetery C	3	4	1.3	90	22.5
Total Cemetery A	50	105	2.1	2479	23.6
Total Cemetery C	9	10	1.1	140	14.0

quantitative estimates made from satellite images of the type attempted for Bāb adh-Dhrā'. At Qazone, an excavated area of 600 sq m contained 21 graves (Politis 1998a: 612, fig. 3), or one grave per 29 sq m. Figure 2 shows a total area looted in 2007 of 80,469 sq m, which would give an estimate of 2775 graves looted. While the figure of 2775 does not precisely match the reported field count of 3500, the estimate is reasonably close to the count, which offers some reassurance about the reliability of quantitative estimates derived from satellite imagery. In the absence of dedicated projects based on some combination of pedestrian survey, high resolution aerial or satellite imagery, and on-the-ground mapping, precise counts will remain elusive. Without a precise field count, it is not possible to determine whether the field estimate or the estimate derived from the satellite imagery represents a more accurate quantification of looting damage. Accurate and thorough survey of even limited areas of the cemetery would allow refinement of the estimate of the density of looted graves (in graves per sq m), and improvement of the estimate of the total number of looted graves derived from satellite imagery.

Results

The examples of Bāb adh-Dhrā' and Qazone show that the pitted areas identified using Google Earth imagery have been extensively damaged by illicit digging. Image-derived quantitative estimates of the damage caused by looting are reasonably accurate at Qazone.

The results of the survey for looted sites are presented in Table 1, where four types are recognized among 25 sites. Type I sites are those already identified as victims of looting (e.g., Bāb adh-Dhrā', Safi, and Faynan). Type II sites are clearly looted, but not mentioned as such in the literature (e.g., Azziya and Dharih). Type III sites do not appear in the literature, but have suffered looting (e.g., Zizia). Type IV sites have possibly suffered some damage from looting, but require on-the-ground verification (e.g., Umm el Abar esh Sherqiye).

Site visits in June 2009 to 16 of the 25 sites were able to confirm that the areas identified were indeed looted in 13 cases, while two of the Type II sites (EDSAS Suwayma 10 and SAAS Site 85) were misidentified and have not suffered looting damage, and at one site (Iktanu) the area identified as looted had been bulldozed and confirmation was impossible. Both cases of misidentification were in areas with imagery of inferior resolution, where in one case piles of backdirt were mistaken for pitting and in another trenching—apparently military, of unknown date—was mistaken for pitting. This ground truthing allowed the discard of one further site identified as potentially looted (SAAS Site 114).

We thus identified a total area of 515,351 sq m (51.5 ha, or ~0.5 sq km) as intensively looted. This is much less than the >15 sq km area that Stone identified in Iraq (2008b: 137), but Jordan is a much smaller and more politically stable country. While much of the looting is relatively small in scale, with looted areas encompassing approximately 1 ha (10,000 sq m), in a handful of cases (Bāb adh-Dhrā', Qazone, and Fayfa) looting is larger in scale, with the mean looted area of these three sites approximating 72,000 sq m. In one case (Safi), the scale of looting is an order of magnitude greater than the majority of sites, and nearly 200,000 sq m have been looted.

Patterning is evident in the dates of the looted sites, with the majority (~95%) of sites dating to the EBA or Roman/Nabatean periods. Establishing the date of looted sites is complicated by incomplete dating records and multi-period occupation, but nevertheless when a looted area is added to the assessment the dominance of EBA sites is apparent, as EBA sites account for 68% of the total looted area. Interpreting this pattern remains difficult, however, as the number of sites of a given period and their visibility and accessibility may influence their targeting, in addition to the saleability of artifacts from those sites. On-the-ground investigation of looted sites, as well as ethnographic research into looting practices of the sort pioneered by Farchakh-Bajjaly (2008a, 2008b), Kersel (2007), Kersel, Luke, and Roosevelt (2008), and Rose and Burke (2004), are obvious further steps. Identifying the pattern represents a significant advance and testifies to the utility of satellite remote sensing for investigation of looting of archaeological sites.

The apparently low number of looted cemeteries (18 out of a possible 406) should not be taken as an accurate estimate of the incidence of looting, as JADIS includes as "sites" even small, isolated groups of burials, and only relatively extensive looting is identifiable on satellite imagery. Thus, the nature of the site database biases the method towards under-estimating the true incidence of looting. In addition, it remains difficult to identify and quantify site damage in urban areas, as well as other kinds of damage other than the illicit excavation of cemeteries (e.g., destruction by agricultural expansion or the mining of tells); this also contributes to under-estimating the extent of looting. Future work will explore ways in which the biasing effect of small sites and visibility limitations can be addressed, and investigate possible archaeological and economic reasons for the apparent targeting of EBA and Roman/Nabataean tombs.

Conclusions

Google Earth is a viable tool for identifying and quantifying archaeological site looting. We have demonstrated that Elizabeth Stone's (2008a, 2008b) methodology can be replicated using publicly-available imagery, at low cost and without the

Figure 4 Aerial photograph of Safi in 1992 (courtesy of the Royal Jordanian Geographic Centre).

expertise-intensive steps of image acquisition, processing, and ground truthing. Its use could multiply the number of individuals and agencies carrying out such monitoring and produce a large quantity of reliable information to feed into the heritage management policy-making process.

Several factors are critical to the success of using Google Earth as such a tool. The first is the availability of high-resolution imagery. The Google Earth imagery can vary in quality by region (Parcak 2009: 43–51). Successful identification of pits or other evidence of intrusive site looting will generally require images that are free of cloud cover and have resolutions of at least one meter per pixel. The second factor is the suitability of the geography, since the method is most effective in arid regions without extensive vegetative cover. Nevertheless, the criterion of open terrain encompasses many areas that have rich archaeological heritage that is suffering from looting (e.g., other southwest Asian countries, the coastal desert of western South America, Afghanistan, Mali). The final factor is the availability of site location data. As anyone who has tried to find their home in Google Earth imagery without labels or landmarks can attest, satellite imagery on its own is so data rich as to be overwhelming. If the imagery is to be visually scanned for looted areas, a spatially explicit database of archaeological sites that can serve as a guide to where to look is critical. Stone had access to the published data of the Uruk, Nippur, and Eridu archaeological survey projects (Stone 2008b: 126). The present study employed JADIS and DAAHL, which served both as guides for where to look and

Figure 5 Google Earth image of Safi in 2004. Areas heavily pitted by looting are outlined in white; compare the appearance of these areas with Figure 4.

indices to the relevant literature for information about looted sites. Some analogous data source is necessary for any project of this type.

At this point, information derived from monitoring Google Earth imagery rarely has diachronic depth, so detailed time series analyses of the type that Stone (2008b) used to track the progression of looting in Iraq beginning in 2003 are not possible. The information does, however, serve the valuable purpose of establishing baseline data, which could be used in the future to identify and quantify new looting. This is precisely the type of application of remote sensing data to cultural heritage management recently advocated by Stubbs and McKee (2007).

A dated baseline would allow the construction of historical context for the looting damage identifiable in recent satellite images through use of reports from previous archaeological investigations, old aerial photographs, and even ground-level photos or eyewitness reportage. For Jordan, several scholars have already demonstrated the utility of aerial photography for archaeology (Kennedy 1996, 1998; Kennedy and Bewley 2003, 2004, 2009; MacDonald 1997), and photographs are available from the Royal Jordanian Geographic Centre and the Aerial Archaeology in Jordan Project Archive at the University of Western Australia's Department of Classics and Ancient History (http://www.classics.uwa.edu.au/about/research/past_projects/jordan_archive, accessed October 16, 2008).In 2008, the latter archive was awarded a grant to facilitate the presentation of its photographs on a dedicated website (http://www.classics.uwa.edu.au/about/research/past_projects/jordan_archive/stop_press__phi_award_for_project, accessed October 16, 2008).

Aerial photographs offer an excellent source of historical comparison, potentially allowing the identification of the time period in which sites were looted. In the case of Safi, for instance, a 1992 aerial photograph from the Royal Jordanian Geographic Centre provides a dramatic contrast with the 2004 Google Earth imagery, clearly demonstrating that much of the extensive looting at Safi took place in the 12-year span between 1992 and 2004 (FIGS. 4, 5). This is corroborated by several field reports (Papadopoulos et al. 2001; Politis 1994, 1998b, 2002; Politis et al. 2005; Politis et al. 2007), and previous aerial photography (Politis 2002: figures 14.6, 14.7), which may be usefully combined with the quantifications of looted area presented here to explore the economic outcomes of looting (Brodie and Contreras in press).

The task of overall survey and regular monitoring is a massive one, and the expansion of this effort to other areas of the world, and, for that matter, its further development in Jordan, may be best accomplished through a coordinated distribution of labor. To achieve that goal, we have presented here a simple methodology and display solution that will allow academic and public participation. The demonstration that looting damage can be identified via Google Earth imagery makes our method two-tiered: simple identifications of looted areas in Google Earth images requires only minimal computing skills, while users with slightly more background can replicate the entire methodology we present. In addition, Google Earth offers a facility for uploading photographs; the searching of remotely-sensed imagery could be improved by archaeologists or concerned members of the public uploading geotagged photographs—images including geographic coordinates—of site damage, which could guide further investigation.

In general terms, the work reported here is intended to be an assessment of the suitability of Google Earth as a tool for monitoring looting, and should not be taken to represent a comprehensive catalog of archaeological site destruction in Jordan. Not all sites included in JADIS, nor all of the existing sites, were inspected, and the true incidence of looting must be higher than suggested here. Nevertheless, we are optimistic about this methodology as a tool for efficiently and affordably improving our understanding of the scale, patterning, and history of the looting of archaeological sites.

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