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Rethinking the Landscape: Emerging Approaches to Archaeological Remote Sensing

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Abstract

An emerging arena of archaeological research is beginning to deploy remote sensing technologies—including aerial and satellite imagery, digital topographic data, and drone-acquired and terrestrial geophysical data—not only in support of conventional fieldwork but also as an independent means of exploring the archaeological landscape. This article provides a critical review of recent research that relies on an ever-growing arsenal of imagery and instruments to undertake innovative investigations: mapping regional-scale settlement histories, documenting ancient land use practices, revealing the complexity of settled spaces, building nuanced pictures of environmental contexts, and monitoring at-risk cultural heritage. At the same time, the disruptive nature of these technologies is generating complex new challenges and controversies surrounding data access and preservation, approaches to a deluge of information, and issues of ethical remote sensing. As we navigate these challenges, remote sensing technologies nonetheless offer revolutionary ways of interrogating the archaeological record and transformative insights into the human past.

INTRODUCTION

For more than a century, archaeologists have relied on remote sensing data sets—ranging from aerial photographs to satellite imagery to terrestrial geophysics—to aid in the discovery, mapping, and interpretation of ancient sites and cultural landscape features. Conventionally, remote sensing technologies have been understood primarily as tools to assist us in doing the real work of archaeology: helping us locate sites in regional surveys or identify promising places to excavate. However, an emerging arena of research is beginning to employ remote sensing as an independent and complementary means of interrogating the archaeological record and, in so doing, is providing insights into the human past that could not be achieved through conventional fieldwork. At the same time, we are witnessing an unprecedented growth in the quality, diversity, and availability of remote sensing data sets and technologies, including new satellite programs offering higher spatial and spectral resolution, increasingly easy access to historical aerial imagery, and expanded lidar (light detection and ranging) and synthetic aperture radar coverage globally, as well as a revolution in field-deployable drones and large-array geophysical instruments. While traditional archaeological fieldwork is becoming increasingly difficult owing to its high costs, volatile geopolitics, and the global pandemic, remote sensing–based investigations offer us a way to undertake pathbreaking research that is nondestructive and can be done quickly and inexpensively, with small teams of people, often entirely remotely.

Following an overview of key data sets and technologies now being employed in archaeological investigations, this review highlights several arenas of emerging remote sensing–based research that are reshaping our understanding of the human past: (*a*) documenting archaeological sites across vast regions, (*b*) mapping the extent of relict land use systems, (*c*) revealing the complexity of settled spaces, (*d*) modeling the environmental contexts of past human activities, and (*e*) protecting cultural heritage across the globe. Alongside these opportunities, this review outlines a range of new challenges and controversies, including how to improve access to and preservation of these digital resources and how to undertake research without drowning in the Big Data deluge, as well as some of the complex ethical questions that these new technologies generate.

REMOTE SENSING TECHNOLOGIES

In this section, I briefly summarize some key archaeological remote sensing resources that are employed in the studies referenced in this review. Numerous recent publications provide more detailed, technical discussions of these various technologies (e.g., Comer & Harrower 2013, Forte & Campana 2016, Hadjimitsis et al. 2020, Johnson 2006, Lasaponara & Masini 2012, McKinnon & Haley 2017, Opitz & Cowley 2013, Opitz & Herrmann 2018, Tapete 2019).

The oldest forms of archaeological remote sensing relied on black-and-white aerial photographs (Hanson & Oltean 2013, Wilson 1982), often derived from government-sponsored mapping programs, while more recent research has made similar use of declassified CORONA satellite imagery (Beck et al. 2007, Casana et al. 2012, Kennedy 1998, Ur 2013) and military surveillance photographs (Hammer & Ur 2019). These images offer high-resolution (1–3-m), stereo perspectives on the landscape and, critically, can preserve a picture of sites and features that predate damage and destruction associated with modern development, but they are highly variable in cost and accessibility. Public satellite programs, including Landsat, ASTER, and SPOT, are usually too coarse in spatial resolution (10–60 m) for direct detection of most archaeological sites, but because they provide multispectral imagery covering the visible to thermal infrared parts of the spectrum, offer decades of coverage dating back to the 1970s, and are freely available in most cases, the images they produce have a range of archaeological applications (Giardino 2011). Other satellite programs, such as AVHRR and MODIS, are even lower in spatial resolution (500–1,000 m) but, by imaging the entire globe on a daily basis, offer a powerful means of modeling the environmental contexts of past human activities. For the past two decades, very high resolution (0.3–2-m) satellite imagery in the visible and near-infrared spectrum has become a valuable tool for identification of sites and features, but because most of this imagery is collected by private companies it can be cost prohibitive, leaving many researchers to rely on the subset of images provided by online services such as Google Earth and Bing Maps. The greater spectral resolution of newer satellites such as *WorldView-3*, as well as the frequent revisit rate of newer imaging satellites such as those operated by Planet, will offer new research opportunities in the future.

Digital topographic data sets are also a key tool in archaeological remote sensing. Satellite-based synthetic aperture radar has been used to produce publicly available but relatively low resolution (15–30-m) global data sets, such as the Shuttle Radar Topographic Mission and the ASTER-derived digital elevation models. Much higher resolution (1–10-m) but costlier imagery is now available from TerraSAR-X and other, similar programs. In forested regions, aerial lidar data collected from aircraft have been particularly important in archaeological research, and many government agencies have begun collecting and distributing these data, but coverage remains highly variable around the world (Opitz & Cowley 2013). Collecting aerial lidar remains cost prohibitive for many researchers, but as the size and cost of lidar sensors continue to decline, it is becoming more feasible, enabling targeted, higher-resolution data collection.

Rapid developments in drone technologies and photogrammetric processing software have transformed archaeological field documentation over the past few years (e.g., Campana 2017a, Wernke et al. 2014), and a new generation of drone-optimized sensors, including multispectral infrared (Hill et al. 2020), uncooled thermal (Casana et al. 2014, 2017, 2020), and microlidar (VanValkenburgh et al. 2020), are offering unparalleled opportunities for ultrahigh-resolution imaging of archaeological sites. Drone surveys are increasingly being undertaken in coordination with terrestrial geophysical surveys using magnetic gradiometry, ground-penetrating radar, electrical resistivity, and electromagnetic induction. Although these technologies have been available for decades, advances in deployment vehicles and processing software are revolutionizing how they can be employed in research projects. In particular, the integration of geophysical instruments with low-cost GPS/GNSS (global positioning system/global navigation satellite system) devices (Hill et al. 2019) and the commercial development of large-array survey packages in which multiple sensors are mounted on carts or other vehicles is making collection and processing of large terrestrial geophysical data sets vastly more efficient (Opitz & Herrmann 2018).

DISCOVERING SETTLEMENT HISTORIES

Although the first regional archaeological surveys were conducted only for the purpose of finding sites for potential excavation (e.g., Braidwood 1937), subsequent research in Peru (Willey 1953), Iraq (Adams 1965), and Mexico (Sanders et al. 1979) helped demonstrate that regional-scale, diachronic analysis of the number, size, and distribution of sites could reveal things about the past that excavation could not. Today, regional-scale investigations of sites and landscapes form a cornerstone of archaeology, enabling explorations of population dynamics over time; the emergence and development of complex societies; patterns of trade, exchange, and movement; and human–environment relationships (e.g., Kantner 2008, Wilkinson 2003). Analysis of aerial photography was always an important tool in regional archaeological surveys because it enabled rapid recognition of sites and features over large areas (e.g., Adams 1965, Kosok 1965). However, in many parts of the world aerial photography was inaccessible or nonexistent, while publicly available satellite imagery was generally too coarse in spatial resolution to resolve individual sites (Limp 1989).

With the growing availability of high-resolution satellite imagery since the late 1990s, researchers have begun to undertake remote sensing–based investigations at spatial scales that are orders of magnitude larger than would be possible through conventional fieldwork, exploring beyond survey boundaries and across political borders. These projects offer exciting new perspectives on settlement histories worldwide.

Regional remote sensing–based surveys have been most effective in areas where archaeological sites are comparatively easy to recognize, owing to their size, state of preservation, and visibility due to land use and land cover conditions. For example, our study of the northern Fertile Crescent uses 1960s-era CORONA satellite imagery to search for sites across an enormous 300,000-km^2 area, encompassing Syria, southern Turkey, and northern Iraq (Casana 2013, 2014b, 2020a,b; Kalayci 2016). CORONA imagery had previously been shown to be a powerful tool for site and feature identification in the region but had been used primarily to aid traditional field survey projects covering areas of a few hundred to a few thousand square kilometers. By undertaking a systematic analysis of the imagery over a much larger area, the project identified more than 10,000 previously unrecorded sites and site-like features, more than tripling the number of known sites in the region. Through analysis of the morphology, size, and distribution of these sites, the project has offered insights into the region's historical and political geography, agro-pastoral practices, and environmental relationships, and has facilitated cultural heritage monitoring efforts. In a similar vein, the Fragile Crescent project closely integrated satellite-based observations with a large regional survey database, providing the basis for research into long-term population trends, the emergence of early urban centers, and the impacts of mid-Holocene climate change (Lawrence et al. 2016, 2017). In the Andes region of South America, the GeoPACHA (Geospatial Platform for Andean, Culture, History, and Archaeology) project has likewise sought to develop a platform to support large, regional-scale, remote sensing–based discovery of archaeological sites and features (Wernke et al. 2020). In Scotland, aerial imagery and high-resolution lidar data are similarly used in a long-running national mapping program to document archaeological sites across the country, producing an extraordinary data set that has powerful capabilities for both archaeological research and heritage management (Cowley et al. 2020).

These projects have been successful in part owing to the relative ease with which archaeological sites and features appear in satellite and aerial imagery in those regions. In areas where sites are less obvious, due to either the nature of the sites themselves or local ground cover conditions, researchers have worked to develop new approaches to aid in their recognition. In Central America, for example, researchers had some success in identifying large sites based on the manner in which they affected vegetation health (Garrison et al. 2008, Miller et al. 1991). Chase et al. (2011, 2012) used aerial lidar to reveal settlements and other cultural features obscured by tree canopy, mapping a vast, previously unknown settlement system around Caracol, Belize. Decades of previous research in the densely forested areas that were the heartland of the Classic Maya had struggled to locate archaeological sites and features outside of the largest monumental centers, impeding understanding of Maya urbanism, political geography, and land use systems. Results of the large-scale lidar surveys pioneered at Caracol were transformative, revealing countless previously unrecorded occupational mounds and other features. Lidar surveys have now been undertaken in many parts of Central America, spurring the development of research consortia and leading to a revolution in our understanding of the region's settlement history (e.g., Chase et al. 2016, Ebert et al. 2016, Fisher et al. 2016, Garrison et al. 2019, Yaeger et al. 2016).

Some researchers have employed increasingly sophisticated approaches to spectral classification or integration of multiple sensors to aid in identifying sites at large, regional scales. Among the most impressive results are those from a study in northeastern Syria by Menze & Ur (2012), who analyze a time series of multispectral ASTER images to identify archaeological sites. While no individual image reveals the sites, the authors' diachronic, phenological analysis can recognize sites with great precision, revealing the location of thousands of both known and previously undocumented sites. Menze & Ur's (2012) methods likely work best in regions where sites and features are easily recognizable in satellite imagery, as was similarly shown to be the case in a study from China that relies on a time-series analysis of Landsat-derived NDVI (normalized difference vegetation index) images (Pan et al. 2017). Even in regions where sites are less evident from space, analyses of high-resolution multispectral satellite imagery alongside drone-acquired imagery have been used to successfully document ancient settlements on the basis of how they impact vegetation, revealing sites in West Africa (Reid 2020), western Greenland (Fenger-Nielsen et al. 2019), and coastal Peru (Vining 2018), and even ephemeral hunter-gatherer sites in Alaska (Keeney & Hickey 2015).

Collectively, these studies show the growing potential of regional-scale satellite and aerial imagery to reveal sites and features that may not be visible otherwise, and to thereby offer unique perspectives on settlement history. Despite these advantages, Wernke et al. (2020) voice a common concern, that remote sensing–based regional investigations "can make no claim to producing results comparable to those of pedestrian survey," because such analyses are inherently biased toward discovery of sites and features that are visible in imagery. But all forms of archaeological data are constrained by parallel issues of bias and visibility; pedestrian survey is only capable of discovering sites and features that are evident to the human eye when looking at the ground. Regional-scale archaeological remote sensing should not be understood as a lesser form of investigation whose results are in some way suspect or provisional until they can be groundtruthed. There are a wide range of observations we make in archaeology that we cannot observe with our eyes, for example, in microscopic analysis of phytoliths or lithic use wear or through instrumental analysis of stable isotopes, geochemistry, or ancient DNA. Similarly, archaeological remote sensing enables observations of phenomena that are too large to observe on the ground, no longer extant, or entirely invisible to the human eye. In this way, we must understand regional-scale remote sensing as an independent, complementary way of interrogating the archaeological record, which has its own potentials and pitfalls but can offer unique perspectives on the human past not attainable through other means.

REVEALING LAND USE PRACTICES

Relict traces of ancient land use practices, including agricultural fields, water management features, road and route systems, and remnants of extractive industries, offer revealing evidence regarding past systems of subsistence, environmental entanglements, and perspectives on labor, gender, and power. However, these frequently ephemeral features can be difficult to recognize using traditional archaeological field methods, as they are often preserved only as subtle differences in soil composition, topographic expression, or vegetation health. Archaeological remote sensing offers perhaps the best means to reveal the extent and character of ancient land use systems (Casana 2014a), a goal that is critical for understanding the long-term environmental impacts of human activities as well as the resiliency of agricultural systems and ecologies in light of a changing climate (Stephens et al. 2019), both of which are core issues in emerging discourses of the Anthropocene (e.g., Bauer & Ellis 2018).

Aerial photographic analysis of past land use features has a long history in Europe (e.g., Wilson 1982). In the Mediterranean basin, ancient field boundaries are often preserved as stone walls, remnant terraces, or stone cairns that can be traced across vast areas of the landscape, often reused for millennia. Careful analysis of their intersection with historic roads, buildings, or settlements enables one to untangle the land use history, as is well illustrated in a case study around Tarragona, Spain (Palet & Orengo 2011). More recent studies have sought to expand on these analyses by employing lidar and other sensors to locate fields in forested areas (e.g., Bernardini & Vinci 2020) or automated detection methods to help identify ancient field boundaries and roadways more effectively (e.g., Traviglia & Torsello 2017).

In the Near East and Central Asia, analysis of historic CORONA satellite imagery (Beck et al. 2007, Casana et al. 2012, Kennedy 1998, Ur 2013), as well as U2 spy plane imagery (Hammer & Ur 2019), has proven to be a particularly valuable resource for investigations of past land use strategies: While remnants of the region's long agrarian history are readily visible from above, in recent decades agricultural intensification and urban development have obscured or destroyed many of these features. In northern Mesopotamia, for example, numerous studies have used CORONA imagery to map extensive traces of radial route systems that surround many archaeological sites (Wilkinson et al. 2010), and analyses of these route systems have helped reconstruct patterns of agro-pastoralism (Casana 2013) as well as the sustainability of agricultural production in light of a changing climate (Kalayci 2016). In the same region, analyses of historical imagery have also revealed vast canal networks built under imperial regimes to supply water to major cities as well as to irrigate crops in this semiarid environment (Rayne & Donoghue 2018, Ur 2018).

In irrigated southern Mesopotamia, construction of canal systems produced a complex palimpsest of relict levees and infilled channels. Maps of these levees and channels based on historical satellite imagery as well as topographic data (Hritz 2010) have helped revise our understanding of agricultural practices at early urban centers (Jotheri et al. 2018). Semi-subterranean qanat (also known as karez) canal systems that are common in semiarid landscapes of Central and Southwest Asia have been mapped using satellite imagery across much of Afghanistan (Stinson et al. 2016). Automated detection of these features, for example, using CORONA imagery in Iraq (Soroush et al. 2020) and Google Earth imagery in China (Luo et al. 2014), has seen some success.

In areas of the world where the ground is obscured by forests, optical imagery is of less value for documentation of ancient land use. Therefore, many researchers working in these areas have turned to aerial lidar to map traces of past agricultural and water management features (Opitz & Cowley 2013). Perhaps the most spectacular recent discoveries have come from the Maya lowlands of Central America, where, as with the detection of settlements, lidar imagery has proven exceptionally powerful at revealing extensive landscapes of terraced agriculture and water management systems (Chase & Weishampel 2016; Chase et al. 2011, 2012; Macrae & Iannone 2016). Stoner (2017) shows that even lower-resolution public lidar can similarly reveal ancient agricultural systems along the Mexican Gulf Coast. These studies demonstrate how areas that today appear to be pristine rainforest or uncultivated scrublands were intensively cultivated agricultural landscapes only a few centuries ago.

In a similar vein, lidar-based investigations have been a transformative resource in Southeast Asia, particularly around the medieval city of Angkor Wat, where extensive lidar surveys have helped reveal a massive network of canals, settlements, and ritual water features throughout the forest (Evans et al. 2013, Klassen & Evans 2020). As public lidar data have become more widely available, lidar-based studies of field systems have begun to proliferate, with examples in Hawai'i (McCoy et al. 2011), Micronesia (Comer et al. 2019), and New England (Johnson & Ouimet 2014), as well as in combination with historical 1930s aerial photography in Wisconsin (McLeester & Casana 2021).

The diverse ways in which traces of past land use strategies are inscribed on the landscape have spurred innovative efforts to locate them, for example, using multispectral imagery analysis (e.g., Ladefoged et al. 2013) or integration of satellite imagery with terrestrial geophysical surveys (e.g., Cajigas 2017, Vacilotto et al. 2020). The emerging interest in documentation of past land use features is transforming our understanding of human–environment relationships globally and offering new perspectives on Indigenous and traditional forms of ecological knowledge; therefore, it will continue to play a key role in archaeological investigations in the future.

EXPLORING SETTLED SPACES

Site-based archaeological remote sensing has been relied upon for decades but has been employed primarily in the service of excavations—as a means to find the best place to excavate. Presciently, Kvamme (2003) argued that archaeological geophysics could instead be used as a form of landscape archaeology—offering us the ability to map traces of past human activity across large areas that are not detectable through other means, thereby providing us with unique insights into the organization of settled landscapes and the cultural construction of space both within and between the areas conventionally delimited as sites. A long-running project centered around the village of West Heslerton in the Vale of Pickering, United Kingdom, illustrates the power of such an approach. Combining more than 1,000 ha of magnetic gradiometry survey data with multispectral aerial imaging, lidar, and large-area excavations, results reveal the complexity of the cultural landscape (Powlesland et al. 2006). Yet, few researchers were able to undertake investigations at a similar scale, largely due to the slow process of terrestrial geophysical data collection, while high-resolution multisensor aerial images remained cost prohibitive in most cases.

While satellite remote sensing can offer critical perspectives on the development of ancient urban centers (e.g., Lasaponara et al. 2016, Stott et al. 2018), large-scale geophysical and drone-based imaging techniques have proven to be even more powerful means of exploring urban environments. Even conventional geophysical surveys, when conducted over very large areas, enable new insights into ancient urban planning, architectural traditions, and movement through cityscapes, with numerous examples from the Near East and Mediterranean (e.g., Branting 2013, Casana & Herrmann 2010, Keay et al. 2009). The emergence of large-array geophysical and drone-based imaging allows such studies to be more easily executed, as in a survey of a medieval walled site in eastern Mongolia that has revealed a wealth of otherwise invisible architectural features (Miller et al. 2019). Similarly, a large study at Tiwanaku, Bolivia, combined drone-based surface mapping with extensive geophysical survey to reveal new insights into the urban layout of residential and ritual areas in the sprawling ancient city (Vella et al. 2019). The ancient urban plans provided by these investigations are spurring interest in the emergent, mutually constituted relationship between urban form and a collective set of social, economic, and political practices (e.g., Fisher & Creekmore 2014).

Beyond individual sites, numerous projects have sought to leverage new technologies to undertake geophysical and low-altitude aerial surveys across large areas, revealing the complexity of the archaeological landscape and many subtle archaeological features that would otherwise go undetected. In the Stonehenge Hidden Landscapes Project (Gaffney et al. 2012), researchers employed a suite of methods to document a large area around the site of Stonehenge, discovering many agricultural and ritual features, including several previously undocumented henges. Similarly, the Emptyscapes project, based around the ancient city of Rusellae, Italy, has sought to use both geophysical and aerial imaging to explore the areas between known sites and features (Campana 2017b). Likewise, extensive geophysical surveys using a variety of instrumentation conducted on monumental earthwork sites and ancient settlements in the Ohio River Valley located a wide range of ancient cultural features, including embankments, wooden enclosures, and storage pits and domestic features, offering a rich perspective of the complexity of these ritual and settlement landscapes (Burks 2014, Henry et al. 2019, Sea & Ernenwein 2021).

Investigations of settled landscapes have seen a growing trend toward integrating multiple sensors and imaging techniques, sometimes collected during different seasonal or land use conditions, to reveal otherwise undetected features. For example, our own research has employed a time series of drone-acquired thermal images, in combination with other forms of remote sensing, to reveal otherwise invisible buildings and earthworks in studies of a Chaco-era settlement in New Mexico (Casana et al. 2014, 2017) and of an ancestral Wichita settlement in southeastern Kansas (Casana et al. 2020). Kvamme's (2006, 2018) investigations at Army City, Kansas, a World War I troop support town, offer an excellent example of how a range of different forms of low-altitude aerial images can be integrated with numerous terrestrial geophysical data sets both to reveal the organization of space at the site and to characterize subsurface anomalies. Likewise, a study at the Enfield Shaker Village in New Hampshire deployed multiple instruments and sensors over several years to provide a much better perspective on the character of subsurface archaeological features as well as the optimal conditions in which to capture them with different instruments (Hill et al. 2020). As these technologies become less expensive, more compact, and easier to deploy in the field, they will offer archaeologists an exciting and productive path forward.

MODELING DYNAMIC ENVIRONMENTS

Many publicly available satellite programs were designed to map geologic features and environmental change; as such, they are often too coarse in spatial resolution to permit direct identification of archaeological sites and features (Limp 1989). However, these data can be a powerful means of exploring the environmental contexts of past human activities, and the increasing sophistication of such analyses offers a critical dimension in archaeological remote sensing.

At a basic level, moderate-resolution multispectral satellite imagery can be employed to characterize the geology of a region, offering insights into strategies for procurement of stones and metals. For example, Borie et al. (2019) successfully use a series of *Landsat 8* images to identify lithic sources across the Atacama Desert in Chile, while Sivitskis et al. (2018) locate sources for chlorite, a soft stone used in vessel production, on the Oman Peninsula through classification of *Hyperion* hyperspectral satellite imagery. These approaches offer a critical lens for understanding regional resource distribution and thus a framework for analyses of raw material extraction, craft production, and trade.

Environmental data derived from multispectral satellite sensors can also inform understanding of patterns in past settlement and land use by revealing the environmental contexts in which sites are located. For example, in Central America, multispectral satellite imagery has long been used to delineate areas of potential settlement within seasonally inundated wetlands, showing the relationship of Classic Maya settlement to the local ecology (Miller et al. 1991). More recently, researchers have sought to integrate multiple sensors and sophisticated image processing to build more nuanced understanding of environmental contexts, as in a study of Tiwanaku, Bolivia, that reconstructed water resources, hydrology, and agricultural potential (Pérez González & Gallego Revilla 2019). Similarly, a study around Padua, Italy, mapped the complex patterns of sedimentation and hydrology in the alluvial plain (Ninfo et al. 2016).

Following trends in remote sensing science more broadly, some researchers are now using a time-series approach that leverages the long history of public multispectral satellite imagery. In the Indus River Valley, for example, Orengo & Petrie (2017) analyze a series of more than 1,700 Landsat images within Google Earth Engine to map relict channels and meander scars, demonstrating the complexity of Holocene fluvial history in relation to human settlement. Multispectral satellite remote sensing data sets with very coarse spatial resolution, such as those derived from the AVHRR and MODIS programs, can also be used to model complex environmental dynamics through phenological analysis of vegetation health. Kouchoukos (2001) employs such an approach to model dynamics of irrigation agriculture in Mesopotamia, while a higher-resolution phenological model of the Near East (Bunker et al. 2016) has been used to estimate agricultural sustainability under hypothesized drought conditions in the past (Kalayci 2016). Likewise, Howey et al. (2014) rely on phenological analysis in the Great Lakes region to model microclimates in which maize cultivation would have been more productive and reliable for past communities. With regard to continental-scale modeling, a study in Tibet deployed satellite-derived, global land cover and elevation models to delineate where barley and millet could have been cultivated under variable climate conditions in the past (d'Alpoim-Guedes et al. 2016). Even more ambitious efforts, including the PAGES (Past Global Changes)/LandCover6k project (Morrison et al. 2021) and the HYDE (History Database of the Global Environment) modeling project (Ellis et al. 2021), are now seeking to develop global models of past land use and environmental change, partly on the basis of global environmental remote sensing data sets.

Collectively, these studies highlight the many ways in which environmental remote sensing data can be leveraged in archaeological research beyond the direct detection of sites and features. Environmental remote sensing approaches like those outlined here provide an essential basis for interpreting patterns in past human settlement and land use; strategies for resource procurement; and, more broadly, reconstructions of dynamic, long-term human–environment interactions at a global scale.

PRESERVING CULTURAL HERITAGE

The growing availability of high-resolution optical imagery derived from commercial satellites has led researchers to begin exploring how these data could aid in documentation of looting and site damage. Such data have become a key resource for cultural heritage management, particularly in times of conflict or in remote regions of the world. In one of the first studies to demonstrate the potential for satellite imagery–based heritage management, Stone (2008) used commercially acquired high-resolution images to document patterns of looting that occurred in Iraq following the 2003 US-led invasion, but the exorbitant costs of imagery acquisition prevented other researchers from undertaking similar efforts. As high-resolution satellite imagery became increasingly easy to access through free, online resources like Google Earth, researchers began to explore the possibilities for investigations of looting and site damage using these data, with successful case studies in Jordan (Contreras & Brodie 2010) and Peru (Contreras 2010).

With the outbreak of military conflict in Syria and Iraq in 2011, remote sensing–based analysis of looting and site damage was given new urgency, as it offered one of the only means of assessing the impacts of war on the rich cultural heritage of the region. In a project undertaken in coordination with the American Schools of Oriental Research and the US Department of State, our team was given access to a large database of continuously updated satellite imagery from DigitalGlobe (now known as Maxar). Using this resource, we undertook a longitudinal assessment of looting and other forms of damage at 5,000 archaeological sites across the study area (Casana 2015, Casana & Laugier 2017). With the global outrage over the wanton destruction of signature monuments and sites in the region, numerous other research teams launched efforts to document archaeological looting and site damage in the Middle East, including the EAMENA (Endangered Archaeology of the Middle East and North Africa) project (Bewley et al. 2016, Fradley & Sheldrick 2017, Rayne et al. 2017), the TerraWatchers project (Savage et al. 2017), and the Afghan Heritage Mapping Partnership (Franklin & Hammer 2018). Researchers working in many other parts of the world have similarly begun to employ high-resolution optical satellite imagery in an effort to monitor cultural heritage, with published studies in Mexico (Morehart & Millhauser 2016), Ethiopia (Khalaf & Insoll 2019), and Cyprus (Agapiou et al. 2017). Satellite-derived observations offer a critical dimension of heritage monitoring by providing systematic assessments of conditions on the ground, even in remote or inaccessible areas. Such studies thus provide key data for both policy makers and cultural heritage specialists by showing, for example, where looting is most common, the types of sites that are most at risk, or how patterns of damage differ across borders.

A key challenge faced by many satellite-based cultural heritage monitoring efforts concerns how to efficiently document the vast number of sites in any given region. Some projects rely exclusively on careful analysis by trained specialists, which is certainly the most labor-intensive process but also is demonstrated to produce high-quality, reliable results (Casana & Laugier 2017). In contrast, the highly publicized GlobalXplorer project (Clynes 2017) sought to crowdsource the identification of looting and site damage, but the unreliability of observations made by volunteers has produced questionable results (Casana 2020b). Researchers have had more success in developing automated protocols for the detection of looting (Lasaponara et al. 2018), as in a study from Afghanistan in which researchers used four-band high-resolution *WorldView-2* satellite imagery to automate recognition of looting holes on several sites (Lauricella et al. 2017). Other researchers have turned to alternative sensors for documentation of looting, particularly a new generation of high-resolution synthetic aperture radar data (Tapete & Cigna 2017), which could be especially useful for monitoring sites in forested or heavily vegetated regions. Kersel & Hill (2019), in contrast, show the value of drone-acquired imagery for close monitoring of highly vulnerable and repeatedly targeted sites, in coordination with local antiquities officials.

As high-resolution satellite and aerial imagery becomes increasingly easy to access, we can anticipate that it will play a growing role in cultural heritage management practices around the globe. A key challenge will be to integrate observational data derived from satellite or other remote sensing data sets into the institutional infrastructure of government agencies tasked with protecting sites; any such efforts undertaken in the context of regional conflicts will inevitably raise a variety of complex political and ethical issues (Pollock & Bernbeck 2018).

CHALLENGES AND CONTROVERSIES

This review of contemporary archaeological remote sensing illustrates the ways in which these technologies are creating a paradigm shift in how we explore cultural landscapes of the past, but they also bring into focus a new set of challenges and controversies. In the following subsections, I outline a few major areas of discourse regarding archaeological remote sensing, focusing on questions surrounding (*a*) data preservation and access, (*b*) approaches to Big Data, and (*c*) ethical remote sensing.

Data Preservation and Access

The many studies highlighted in this review demonstrate the enormous power of satellite and aerial remote sensing data sets for a wide range of archaeological investigations. While these data are more accessible now than in the past, creating more equitable mechanisms for data access and platforms to ensure preservation of ever-expanding data sets remains a serious challenge.

Historical aerial photography and satellite imagery derived from legacy government programs in many parts of the world have now been declassified but often remain difficult or impossible to access. The declassification of CORONA satellite imagery in 1996 included a mandate for its distribution by the US Geological Survey, ensuring its availability and facilitating efforts like the CORONA Atlas Project (Casana 2020b, Casana et al. 2012). However, the declassification of successor satellite programs and U2 spy plane imagery contained no such distribution requirement, making access to the imagery difficult and high-quality digitization of the film impossible (Hammer & Ur 2019). Similarly, the vast archives of aerial photography from the 1920s and 1930s that are held by government and private organizations around the world are even more difficult to access, and there has been little effort to preserve the slowly degrading acetate film, despite its proven value for a wide range of research initiatives in archaeology and beyond (e.g., McLeester & Casana 2021).

Access to modern high-resolution imagery is also problematic, primarily because most such imagery can only be acquired from private companies at very high cost. While we increasingly recognize the value of high-resolution imagery for a host of humanitarian goals, including monitoring cultural heritage, tracking environmental change, and disaster relief, the cost of such imagery means most researchers rely on whatever data Google Earth or Bing Maps elects to post on its platform, preventing longitudinal analyses or rapid response to threats. The largest commercial satellite imaging company in the world, Maxar (formerly DigitalGlobe), derives most of its business from the US Government, which tasks satellites with a wide range of intelligence and defense goals; but, through a decades-old agreement, the firm is able to then resell the same imagery to researchers, despite it having already been purchased using public taxpayer dollars. This imagery should be regarded as a public resource and made freely available for nonprofit research in the same manner as other publicly funded imagery acquisitions.

For the host of other forms of aerial and terrestrial remote sensing data, we face major hurdles in how to ensure ongoing preservation and access to these unique data sets. We should urge policy makers to invest more in infrastructure initiatives (Kintigh et al. 2016) as well as develop our own strategies to ensure that digital data remain viable and accessible in the future (Kansa & Kansa 2018). While efforts to make data increasingly accessible and free are laudable, many researchers fear that these data could also offer a road map to looters, providing unfettered information on the location of vulnerable archaeological sites. In the United States and many other countries, archaeological site locational data are closely guarded by state agencies and provided only to authorized researchers and professionals for limited periods of time. But as emerging remote sensing technologies make site identification easier, and as digital file sharing makes sharing of such data sets seamless, strategies to protect sites by limiting access to official files are becoming less and less effective. At the same time, many scholars have begun to argue that sharing site information with stakeholders and community members is an essential step toward decolonization of the discipline. Thus, whether and how to provide public access to huge data sets that can potentially reveal the location of countless otherwise unprotected archaeological sites remain an unresolved and challenging issue (Chase et al. 2020, Gupta et al. 2020).

Approaching Big Data

Faced with a continuously expanding arsenal of remote sensing data sets, a rising tide of recent research has followed broader trends in imagery analysis and computer science in attempting to develop alternative means of analyzing data, experimenting with automated, machine learning–based approaches or, alternatively, with crowdsourcing and citizen science to aid in site discovery and analysis.

Crowdsourced approaches to archaeological discovery may be good mechanisms to engage the public in research projects and can offer strong experiential learning opportunities for students, but their efficacy in actually locating archaeological features or documenting looting and site damage is far more dubious. For example, a large crowdsourced effort to locate Genghis Khan's tomb managed to recruit 10,000 volunteers who spent a collective 30,000 hours examining small, random tiles of satellite imagery in Mongolia (Lin et al. 2014). The crowd identified 2.3 million potential targets, but the research team was able to confirm only 53 of them as archaeological sites, a result that likely could have been achieved much more easily and with greater confidence by a single specialist researcher in a matter of hours. Notwithstanding these questionable results, Parcak (2019) adapted essentially the same methodology in the GlobalXplorer project, which seeks to both identify sites and track looting around the world. Despite the substantial funding and publicity the project has garnered (e.g., Clynes 2017), and despite its claims of success (Parcak 2019, pp. 219–28), the results of the project have yet to be published in a manner that would facilitate their evaluation. The evidently poor results of these well-funded crowdsourcing efforts are mirrored by more-controlled studies (Stewart et al. 2020), largely because volunteers routinely produce so many false positives in their assessments that their results are analytically useless.

In contrast, automated machine learning–based approaches, which employ both spectral and spatial characteristics of known sites or features to automatically extract similar phenomena from a larger imagery data set, are increasingly showing promise. The most successful efforts to date are those that have sought to identify sites or features of fairly uniform size and shape, such as stone-built tombs in Oman (Harrower et al. 2013), circular ritual enclosures in Sweden (Trier et al. 2009), earthworks in Tonga (Freeland et al. 2016), Roman forts in Tunisia (Bachagha et al. 2020), and cache pits in Michigan (Howey et al. 2020). Although they have demonstrated some success, these projects are able to recognize only specific types of known sites and features in particular environmental contexts; thus, they cannot be exported easily to other regions. More ambitious projects that seek to recognize a greater range of sites and features across more diverse landscapes face significant challenges owing to the ambiguity of what constitutes a site, how it is manifested on the ground, and how it has been recorded (e.g., Lambers et al. 2019). Moreover, even as automated detection tools become more powerful, they will not replace the interpretive role of archaeologists, who are needed to make meaning from observations as well as to recognize unique or unexpected features. In many cases, the time and resources invested into developing automated site detection methods may be better spent by simply undertaking a more conventional brute-force approach, relying on a dedicated team of expert analysts to explore imagery systematically and document the archaeological features it may contain (Casana 2014b, 2020b). Nonetheless, as the quantity and resolution of remote sensing data sets continue to expand, archaeologists will face ongoing challenges in how to incorporate these Big Data into research initiatives (Bevan 2015, McCoy 2017).

Ethical Remote Sensing

With the increasing adoption of remote sensing as a transformative technology in archaeological research, some scholars have begun to raise ethical and legal questions about our responsibilities in undertaking these investigations (Richardson 2018, VanValkenburgh & Dufton 2020). Critics have problematized the seemingly omniscient perspective remote sensing data can provide, which can appear stripped of cultural context and the meaning or experience of place (e.g., Millhauser & Morehart 2016). In a worst-case scenario, access to remote sensing data are also largely restricted to elite academics in wealthy countries (Bevan 2015, Opitz & Herrmann 2018), potentially reproducing colonial and imperial modes of engagement and understanding. Scholars have similarly questioned the ethics of relying on remote sensing technologies that derive from military and intelligence programs, particularly in regions of the world that are engaged in war (e.g., Pollock & Bernbeck 2018). These scholars ask whether employing such resources in archaeological research could make us complicit in the conflict or even endanger civilians.

In some respects, aerial lidar– and drone-acquired imagery create distinct ethical challenges in that, rather than simply analyzing preexisting remote sensing resources, they involve active data collection over sometimes large areas of the landscape without much of the government oversight or stakeholder involvement that conventional archaeological fieldwork typically requires.

Numerous researchers have raised questions around the ethical acquisition of aerial lidar and drone imagery, arguing for more direct community engagement as well as for efforts to ensure the resultant data are publicly accessible and combined with outreach and education efforts (Cohen et al. 2020, Fernández-Diaz et al. 2018, Kersel & Hill 2019). Fredheim (2020) argues, however, that simply making data open access does not address the ethical issues inherent in our work. Likewise, Chase et al. (2020) point to the potentially problematic issue surrounding making data too easily accessible, as they reveal the location of countless otherwise hidden archaeological sites, exposing them to potential looting.

The ethical issues raised here are not unique to archaeological remote sensing—they are fundamental questions regarding the discipline as a whole. As with many other aspects of archaeology, it is essential for us to remain cognizant of what our work means in terms of ownership for stakeholders, particularly when working in occupied territories and conflict zones and on issues that intersect with nationalist agendas or claims by Indigenous and historically marginalized communities. But to push back against some critics, we also must recognize that remote sensing–based archaeological investigations are replicable, nondestructive, and noninvasive, rendering them transparent and democratizing in ways that are rare in the discipline. Rather than not using these powerful tools for research, archaeologists who are concerned with efforts to decolonize the discipline should work to make these technologies more easily accessible, investing in training and infrastructure. Archaeological remote sensing can be done by anyone with basic technical skills, anywhere in the world, without the expense and bureaucracy of traditional fieldwork; it takes only data and leaves only footprints (at the most), while providing us with powerful ways of investigating past societies.

CONCLUSION: UNEXPLORED HORIZONS

This review has sought to highlight key arenas of contemporary research in archaeological remote sensing that do not merely provide support to conventional fieldwork but rather offer transformative new ways of investigating the human past. These studies show that it is possible to document archaeological sites and relict land use features across vast regions; they enable us to peer into the organization of space within ancient settled landscapes; they reveal the environmental context of past human activities in ways that could not be achieved otherwise; and they offer a powerful new tool for proactive monitoring of archaeological sites and monuments, even in conflict zones and remote regions of the world. Invariably, the disruptive nature of these new technologies raises a host of theoretical, technical, and ethical questions that we are still working to fully understand and adequately address, but it is difficult to understate the opportunities they provide for the future of archaeological research.

As remote sensing technologies continue to improve, we are likely only at the beginning of a revolution in its possibilities for archaeological research. While some scholars have lamented diminishing rates of archaeological discovery around the globe (Surovell et al. 2017), emerging approaches to remote sensing offers the opportunity to begin exploration of landscapes that have until now been beyond reach. Improved drone- and satellite-based sensor technologies could enable us to discover cultural features in areas of the landscape with extremely low archaeological visibility, such as temperate woodlands and rain forests as well as below sand, ice, and snow. Improved subsurface remote sensing could begin to reveal the enormous number of archaeological sites that likely lie buried below sediments in river valleys or hidden in unknown caves. Settlements, shipwrecks, and other submerged archaeological remains are likely preserved in huge numbers around the world, but high costs and technological challenges have largely prevented large-scale underwater archaeological surveys. Rapid-response, high-resolution satellite imaging could transform heritage monitoring efforts by becoming a proactive tool for policing looting and destruction, rather than a passive, post hoc undertaking. While we are collectively saddened by the rapid destruction of archaeological sites and features around the world through development, agriculture, and looting, as well as by the diminishing possibilities for traditional archaeological fieldwork driven by conflict, disease, and funding shortfalls, remote sensing offers opportunities for discovery of the human past that we are only beginning to realize.

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