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Monitoring Islamic Archaeological Landscapes in Ethiopia Using Open Source Satellite Imagery

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ABSTRACT

The African landscape is set to change dramatically in the coming years, and will have a detrimental impact on the inherent archaeological and cultural heritage elements if not monitored adequately. This paper explores how satellite imagery, in particular open source imagery (Google Earth, multispectral satellite imagery from Landsat and Sentinel-2), can be utilized to monitor and protect sites that are already known with particular reference to Islamic archaeological sites in Ethiopia. The four sites used are in different geographic and geomorphological areas: three on the Somali Plateau (Harlaa, Harar, and Sheikh Hussein), and one on the edge of the Afar Depression (Nora), and have varied histories. The results indicate that open source satellite imagery offers a mechanism for evaluating site status and conservation over time at a large scale, and can be used on data from other areas of Africa by heritage professionals in the African continent at no cost.

KEYWORDS

Ethiopia; Islamic archaeology; Africa; satellite remote sensing; GIS

Introduction: Remote Sensing in African Archaeology

The use of satellite remote sensing and aerial photography is common practice within many archaeological research projects across the globe, generating important discoveries and helping scholars understand the historical landscape. As satellite technology improves and spatial and spectral capabilities advance, so does the ability to identify past human activity. While much of the current literature explores archaeological site detection through satellite remote sensing (Campana 2003; Georgoula et al. 2004; Ricchetti 2004; Aminzadeh and Samani 2006; Lasaponara and Masini 2006, 2007; De Laet, Paulissen, and Waelkens 2007, 2009; Masini and Lasaponara 2007; Grøn et al. 2011; Agapioų et al. 2013), this paper explores how satellite imagery, in particular open access imagery, can be used to monitor and protect sites that are already known with particular reference to four Islamic archaeological sites in Ethiopia that are the focus of comparative research being completed as part of the "Becoming Muslim" European Research Council Advanced Grant funded project (694254 ERC-2015-AdG) in which Khalaf is post-doctoral researcher and Insoll, principal investigator.

This research project is assessing conversion to Islam and Islamization processes in eastern Ethiopia through archaeological excavation and survey at a range of sites, particularly Harar, Harlaa, and their surrounding regions. This is permitting evaluation of rural and urban Islam, pilgrimage and shrine-based practice, mosque architecture, the veneration of saints, and changes in lifeways through, for example, changes in diet, and the adoption of Arabic epigraphy and Muslim burial. Early and comparative evidence for the connection between Islam and long-distance trade, manifested through the appearance of imported artifacts indicating participation in largely Muslim-dominated Red Sea and western Indian Ocean networks, is also being explored (Insoll in press; Insoll and Zekaria in press).

In general, very little research has been completed on Islamic archaeological sites in Ethiopia. The need to preserve and record the sites discussed here is therefore paramount, as so little is known about Islamic archaeology in Ethiopia in comparison to other aspects of later Iron Age or medieval archaeology such as Christian or late-Classical sites (Insoll 2003, 2017a; Phillipson 1998, 2009; Finneran 2007). The aspect of the research described here has arisen from the need to remotely monitor the status of the sites investigated without constantly being in the field, as changes to the sites have been rapid even since the start of this research project in 2014.

The current danger to archaeological sites in Africa, Islamic or otherwise, comes from an increase in urbanization and infrastructure projects (Kankpeyeng and De Corse 2004; Folorunso 2008; Bordes et al. 2008; Arazi 2009; Lane 2011). Environmental challenges are also a factor, including erosion, flooding, and desertification (MacEachern 2001; Arazi 2011; Marchant and Lane 2014; Lane 2015; Marchant et al. 2018), as is looting (Parcak et al. 2016; Fradley and Sheldrick 2017), which although not documented, is also the case at important sites in Ethiopia. There is also a threat to sites where conflict is lower level and less well-documented, as for example in Mali (Martinez 2015; Joy 2018). Remote sensing datasets and GIS databases have more recently been used to monitor sites of historical importance, and have documented various human activities as threat to sites including agriculture, development (roads, railways, etc.), mineral extraction, and looting (Parcak 2007, 2017; Contreras and Brodie 2010; Brodie and Contreras 2012; Casana and Panahipour 2014; Agapiou et al. 2015; Nebbia et al. 2016; Parcak et al. 2016; Casana and Laugier 2017; Rayne et al. 2017).

Land use and land cover change studies using satellite imagery have documented the rapid increase in urbanism and infrastructure throughout various countries in Africa (Yin et al. 2005; Angel et al. 2011; Forkour and Cofie 2011; Mundia and Murayama 2013; Debolini et al. 2015; Fenta et al. 2017).

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This rapid growth means that the archaeological record is under threat due to loss of information from various construction projects, expected to support the growth of population across Africa. Developing countries in Africa are projected to have a greater urban population than rural by 2050, with more than half of global population growth expected in the continent (Cohen 2006; Montgomery 2008; United Nations Department of Economic and Social Affairs 2017; United Nations Population Division 2017; United Nations World Urbanizations Prospects 2018). Rapid urban expansion in developing African countries is often unplanned (Tewold and Cabral 2011; Mundia and Murayama 2013), which poses a great risk to existing and as-yet-undiscovered archaeological sites. This destruction is partially mitigated by salvage/preventive archaeology; however, the extent to which this is implemented varies significantly across Africa (Mcintosh 1993; MacEachern 2001; Arazi 2009; Bedaux et al. 2011). In Ethiopia, preventative archaeology in advance of some major construction projects is being completed. For example, the Addis Ababa to Djibouti railway saw archaeological survey completed on parts of the route in the Afar Rift Valley, and similar survey was undertaken ahead of the building of the Gibe Dam (6°50'52.32"N, 37°18'6.78"E) in Ethiopia. However, the results are unpublished, and generally inaccessible (see Ethiopian Electric Power Corporation [2010] for an exception).

The African landscape is set to change dramatically in the coming years, which is predicted to have a detrimental impact on the inherent archaeological and cultural heritage elements if not monitored adequately. The potential of remote sensing to achieve effective monitoring has been highlighted by Magnavita (2016, 116), who has described the benefits of using satellite imagery, airborne survey, and ground-based geophysics in the African context.

Satellite remote sensing in African archaeology has been generally used in areas where surface and sub-surface archaeological remains can be seen on the ground either through crop marks or visible features; this approach often requires high-resolution satellite imagery. The use of high-resolution satellite imagery in particular is undoubtedly one of the most useful sources of aerial imagery data short of flying a plane or unmanned aerial vehicle over a selected study region (Lillesand, Kiefer, and Chipman 2015). Spatial resolution of an image is defined by pixel size. High-resolution imagery is taken using satellite systems in orbit around the Earth that capture data at < 4 m per pixel, meaning that features on the ground less than 4 m in size can be seen.

Readily obtainable examples of high-resolution satellite data are illustrated within the Google Earth application, although in many areas of the African continent, the imagery is not updated regularly. Raw high-resolution satellite imagery is available globally for download at a cost, which, for example, was around $250 per 25 km^2 from Harris Geospatial Solutions (www.mapmart.com) in June 2018 with educational discount and for existing rather than tasked imagery. These costs are prohibitive for most African heritage professionals, but the Digital Globe foundation (http://foundation.digitalglobe.com/) offer grants for individuals at university-level academic institutions for imagery and expertise for their research, which is a possibility for African scholars if they are eligible.

Currently, there are few examples of satellite remote sensing and GIS being utilized in African archaeology (Katsamudanga 2009; Sadr and Rodier 2012; Gaber et al. 2013; Harrower and D'Andrea 2014; Hunt and Sadr 2014; O'Regan, Wilkinson, and Marston 2016; Reid 2016; Sadr 2016), but it has been more widely applied in Saharan/North African contexts where the archaeological remains can be easier to see (Moussa 2001; Mattingly and Sterry 2013; Merlo, Hakenbeck, and Balbo 2013; Shaltout and Ramzi 2014; Mattingly, Sterry, and Edwards 2015; Parcak et al. 2016; Biagetti et al. 2017; Rayne et al. 2017). A notable example of its application and use in this area being provided by the EAMENA Project (Bewley et al. 2016).

In contrast, there are many studies that show the benefits of using satellite remote sensing for archaeological research outside the African continent (Beck et al. 2007; De Laet, Paulissen, and Waelkens 2007; Lasaponara and Masini 2007; Garrison et al. 2008; Siart, Eitel, and Panagiotopoulos 2008). Most, if not all, of the case studies use high-resolution imagery such as IKONOS and QuickBird, which have a high cost. The focus here is on four open access satellite imagery sources. First, the application Google Earth (and Google Earth Engine) is open access software available for download that gives viewers a representation of the earth based on satellite imagery. This software has boosted so-called "armchair archaeology" where anyone can use Google Earth to identify undiscovered archaeological sites (Australian Geographic 2013). The other types of satellite imagery used come from three different medium-resolution sensors; two of these sensors are currently in orbit (Landsat 8 and Sentinel-2) and one has been decommissioned (Landsat 5 TM). These medium-resolution sensors are not traditionally used for archaeological research, because the spatial resolution is not great enough to detect archaeological sites. However, these sensors are used to analyze features of the landscape for accurate mapping (Gong et al. 2012), particularly urbanism (Li, Gong, and Liang 2015; Poursanidis, Chrysoulakisa, and Mitrakaab 2015), cultivation and vegetation (Fan et al. 2015; Schwieder et al. 2016), and detecting change in the landscape over time (Thomas et al. 2011; Son et al. 2015). These qualities can enable the identification of landscape dynamics that might be a threat to archaeology in the future.

Study Area

The four Islamic sites in Ethiopia discussed are Harlaa, Harar, Nora, and Sheikh Hussein. The rationale for their selection is that they represent different types of Islamic sites in Ethiopia. Harlaa is an abandoned partly-Muslim trading settlement connected to the Somaliland coast and western Indian Ocean trade networks. Harar is an extant Muslim city. Nora is an abandoned Muslim settlement connected with the Sultanate of Ifat, and linked to the northern Tigray and Dahlak Islands centered Red Sea trade networks. Finally, Sheikh Hussein is an important pilgrimage center attracting visitors from across the region.

The sites are in different geographic and geomorphological areas, as indicated in Figure 1. Three are located on the Somali plateau. Harlaa is located at 1700 masl on the edge of the main fault escarpment of the southern Afar margin, which is characterized by deeply incised terraces stretching more than 20 km (Pizzi et al. 2008; Coltorti et al. 2015) (FIGURE 1). The landscape can be described as savannah, with scattered trees and grassland. Harlaa itself is heavily vegetated with *Catha edulis* plantations. Harar is further south in the Somali plateau, where there is less terracing

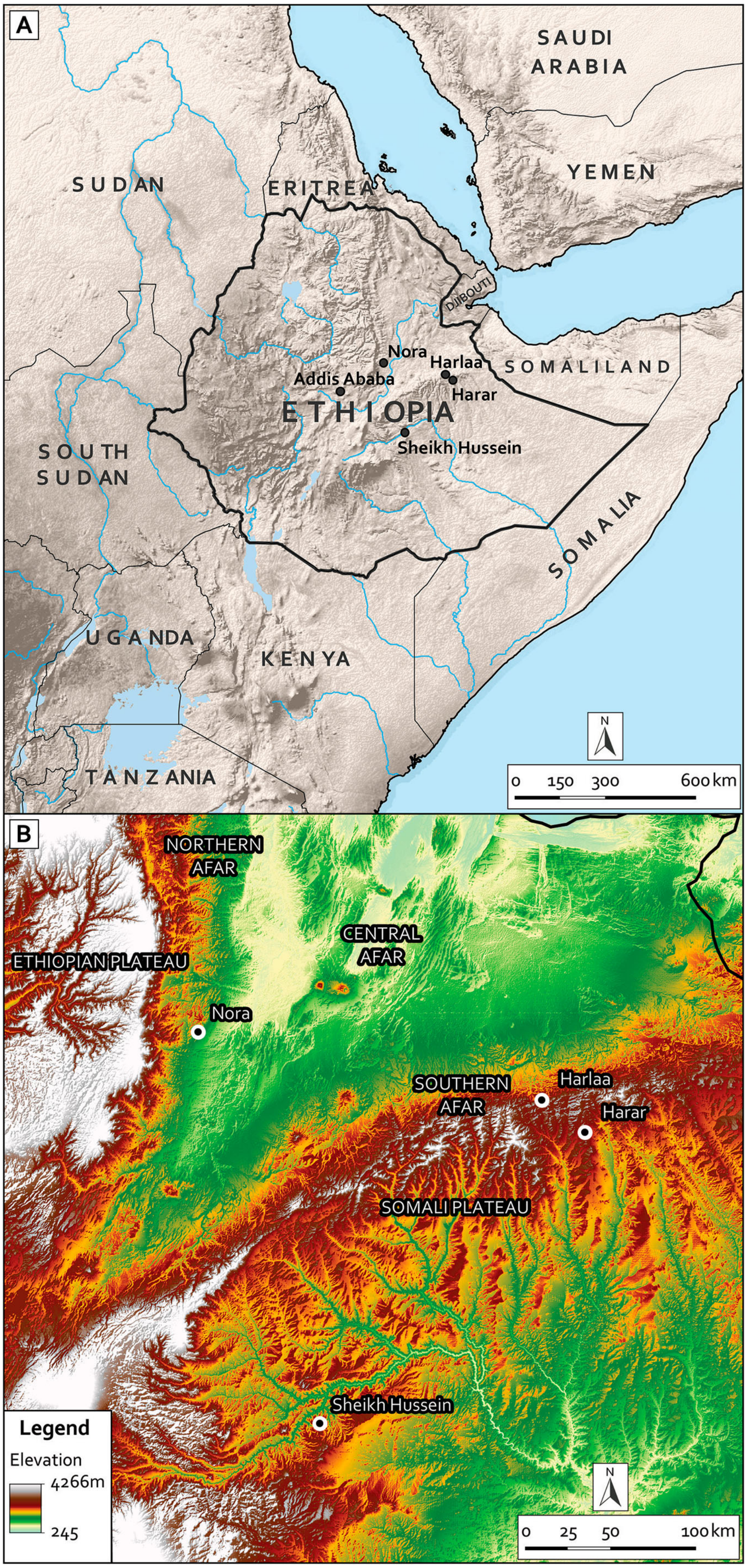

Figure 1. A) The site locations. (Produced by Khalaf.) B) Digital Elevation Model (Shuttle Radar Topography Mission [SRTM]) of the study areas with the main geomorphological features labelled. Map adapted from Corti and colleagues (2015, 252), and produced by Khalaf.

but more vegetation than in the Harlaa region. The elevation is ca. 1800 masl. Nora, like Harlaa, sits on the edge of the Afar depression, but on the central rim, on the opposite side from Harlaa. The landscape has scattered trees, mainly following ephemeral fluvial channels and sits at around 1100 masl. Sheikh Hussein is the farthest south. It is located at 1500 masl and is in a dry zone with savanna type tree and grass cover (Agizew and Abegaz 2015). These sites, though the only examples of Islamic sites archaeologically investigated in Ethiopia, are representative of the types of threats faced by many other archaeological sites in Ethiopia, such as urbanism (Harar), infrastructure development (Nora), population growth and looting (Harlaa), and the impact of farming and environmental change (Sheikh Hussein).

The impetus for using remote sensing as a monitoring tool at Harlaa stemmed from an extensive field walking survey which indicated that significant areas of archaeological remains (ca. 6th/7th to 14th/15th centuries A.D.) had been destroyed to obtain stone for reuse in modern building (Insoll et al. 2017). As indicated in Figure 2a, borrow pits were frequently encountered with adjacent cairns formed of stone blocks awaiting transport to building projects. To assess the extent of site destruction in the recent past, open access remotely sensed imagery was consulted. It was apparent that this imagery was a very useful tool for monitoring the threats Harlaa faced and the study was extended to assess more generally the suitability of open access remote sensing datasets for investigating the conservation of the other three examples of key Ethiopian Islamic sites. Some key issues were considered. First, whether the datasets available were suitable for assessing landscape change over time and if they could be used to pinpoint potential risk to the sites (anthropogenic and environmental landscape change). Second, if remote sensing was a cost-effective tool that could be implemented in the professional Ethiopian heritage context for site assessment and monitoring.

Harlaa (9°29'10.22"N, 41°54'36.96"E)

Harlaa is located on the Harar road within the Dire Dawa City Administration area, ca. 15 km southwest of Dire Dawa, which is the fourth largest city in Ethiopia with a 2007 census population figure of 233,224 (The World Bank 2007). The archaeological site is under and surrounding the modern Oromo village of Ganda Biyo. It is referred to here as Harlaa, as this is the accepted name for the archaeological site and is related to the common appellation of "Harla" given to ruined stone-built towns and funerary monuments, whose origins were ascribed by the Oromo to a legendary ancient people of giant status (Chekroun et al. 2011, 79), and who occupied the region before the Oromo arrived (Joussaume and Joussaume 1972, 22).

Harlaa is archaeologically significant because it has provided an archaeological sequence of up to 2.5 m depth that has been AMS radiocarbon dated to between the 6th/7th and 14th/15th centuries A.D. (Insoll, MacLean, and Engda 2016; Insoll et al. 2017). The site is formed of various components: settlement, cemeteries, mosques, and a defensive wall. Excavation has been completed between 2015–2018 in four areas, including a housing area, jewelry workshops, burials, and a mosque (Insoll, MacLean, and Engda 2016; Insoll et al. 2017). Extensive evidence for participation in both regional and long-distance Red Sea and Indian Ocean trade networks, currently undergoing analyses, has also been recovered. The material includes, for example, glazed ceramics of likely Egyptian and Yemeni provenance; glass vessel and bracelet fragments of probably similar origin; glass and agate beads, including examples visually analogous to Khambhat (Gujarat, western Indian) heat altered carnelian beads; cowry shells from the Indian Ocean and Red Sea; and Chinese Qingbai and Celadon porcelain sherds (Insoll 2017b). International trade routes appear to have been directed toward Zeyla on the Red Sea.

Excessive flooding in the Dire Dawa area has been relatively well documented (Demessie 2007; Alemu 2009; Billi, Yonas, and Ciampalini 2015) and has also exacerbated erosion of various archaeological features in Harlaa, including burials, tomb complexes, pits, and sections of the defensive wall surrounding part of the site (Insoll 2018; Insoll, MacLean, and Engda 2016; Insoll et al. 2017). Besides extraction of stone for construction, further damage to the archaeology has been caused by constructing revetments for field terracing. Building the field terraces for growing subsistence crops, primarily millet, and cash crops, particularly qat (*Catha edulis*), has led to extensive landscape alteration as shown in Figure 2b, and has involved both removal and truncation of the archaeological deposits. Some localized looting of archaeological material has also occurred with ceramics, coins, and beads removed during farming activities, as well as in more targeted form if objects such as coins are found.

Harar (9°18'33.21"N, 42° 8'15.84"E)

Harar is situated ca. 35 km southeast of Harlaa. It is the capital of the Harari People's National Regional State and in 2007 had a population of 99,368 (The World Bank 2007). Harar is located at 1900 masl, and has at its core a historic city, surrounded by a wall (the *djugel*). This is built of locally quarried calcareous tuff (Hashi stone) mortared with mud and wooden reinforcements (Ahmed 1990, 321). It encompasses an area of ca. 1000 × 800 m and is accessed by five gates, with a corresponding district of the city (Horton 1994, 195). The walled city contains within it approximately 2000 houses, 82 mosques, and numerous saints' tombs and shrines (Interuniversity Research Center for Sustainable Development and Harari People National Regional State 2003), the result of important urban development over many centuries (Insoll 2017a).

The walled city was given World Heritage status by UNESCO in 2006 (UNESCO n.d., "World Heritage List"). Increasing urbanization is the primary threat to Harar and UNESCO recognizes that construction and infrastructure development pose potential threats to the conservation of the djugel, the city within, and the immediately surrounding area (UNESCO n.d., "World Heritage List"). Excavations at nine locations in and immediately adjacent to the walled city (five mosques, one shrine, two settlement areas, and one blacksmithing location) have provided AMS radiocarbon dates between the 15th and 19th/early 20th centuries A.D. (Insoll 2017a; Insoll and Zekaria in press).

Harar functioned as a trade center that connected the eastern Ethiopian highlands, arid lowlands, and the Gulf of Aden and it was also a center of Islamic learning and focal point of local shrine-based Muslim practice (Braukämper 2004; Insoll 2017a). The city was capital of the sultanate of Adal (ca.1415 to 1577), powerbase of Ahmad Gragn (b. 1506) in the *jihads*

Figure 2. A) Extraction of archaeological building stone for re-use in construction in Harlaa; and B) the heavily terraced and altered landscape of Harlaa village looking south (Photos by Khalaf).

he led against the Ethiopian Christians, and subsequently an autonomous emirate until it was annexed into the Ethiopian Empire in 1886 (Caulk 1977; Braukämper 2004; Insoll 2017a). The city continues to have a significant regional Muslim religious role and is a focus of tourism (Briggs 2015, 441–454).

Sheikh Hussein (7°44'59.78"N, 40°42'0.05"E)

The Sheikh Hussein shrine is in the eponymous town of Dire Sheikh Hussein in the northern Bale zone of Oromia region near the Wabe Shabelle River. The Sheikh Hussein shrine, or "Anajina" in Oromo, is a significant Muslim center in the Horn of Africa drawing visitors from across the region to annual pilgrimages, particularly to the main festival on the birthday of Sheikh Hussein (Trimingham 1952, 253; Braukämper 2004, 141). Sheikh Hussein is credited with bringing Islam to Bale, possibly in the 12th century, and traditions state that his grave became the subject of pilgrimage soon after his death (Østebø 2012, 52). Braukämper (2004, 144) argues that for those without the means to go on *hajj*, pilgrimage to Sheikh Hussein was regarded as a "substitute." The site is formed of various elements including walled courtyards (e.g., Jajaba Maw-lid), mosques (e.g., Zuktum Mosque), shrines (e.g., Sheikh Ibrahim Ibn Malka), a large prayer shelter (Bokole), and ponds constructed to store water (e.g., Haro Lukka) (Østebø 2012; Agizew and Abegaz 2012, 2015).

The site is representative of regional shrine-based ritual practices and archaeological investigation to assess the chronology of its foundation and use is required, though the standing architecture has been recorded (Agizew and Abegaz 2012, 2015). The shrine is on the UNESCO tentative list of World Heritage sites (UNESCO n.d., "Tentative List"). Other Islamic sites reported from the surrounding region include the ruined Balla mosque 2–3 km south, which, according to local sources, is of 11th century date (Østebø 2012, 52), and the undated Harota Kibla cemetery with Arabic inscribed stelae

(Agizew and Abegaz 2012, 33). Traditions of past peoples probably similar to the Harla are also manifest in this area of southeast Ethiopia where "Sharalla" could be a corruption of "Harla" or "Harala" (Østebø 2012, 47). The Balla mosque clearly belongs to the same architectural tradition as the Harlaa and Nora mosques and is built of similar regular stone blocks (Østebø 2012, illustration 2). The primary threat facing these monuments is from increased farming, and environmental change associated with deforestation.

Nora (09° 50'52.81"N, 40° 3'05.27"E)

Weissiso-Nora, shortened to "Nora" in the Amhara region, is one of a group of sites that attest "strong Islamic influence" (Tilahun 1990, 314) in northeastern Shoa, at the heart of the former sultanate of Ifat (late 13th to early 15th centuries A.D.). Nora appears to have been part of northern directed trade routes through Tigray and onto the Red Sea at Massawa and the Dahlak Islands (Insoll 2003), but it is also possible that the settlement was connected via trade routes across the Rift Valley to the eastern Highlands, and potentially to Harlaa.

Nora has been partially excavated (Fauvelle-Aymar et al. 2006a, 2006b). Covering an area of ca. 15 ha and on a defensible rocky spur, the ruined town appears to have been spatially organized around the main mosque (Fauvelle-Aymar et al. 2006b). Excavation in this mosque provided a radiocarbon date of CAL A.D. 1165–1298 (Fauvelle-Aymar and Hirsch 2010, 36). The house walls were built of mud mortar and stone slabs shaped on their internal and external faces and ca. 60 cm thick. An associated cemetery was also recorded (Fauvelle-Aymar et al. 2006a, 154–155). Rapid infrastructure development is occurring in close proximity to the site with the construction of a new railway and construction and feeder roads, and associated new settlement.

Data and Methodology

The open access satellite imagery used to assess these sites was composed of Google Earth and Google Earth Engine imagery, multispectral satellite imagery from Landsat 5 TM, Landsat 8 and Sentinel-2.

Google Earth and Google Earth Engine

Google Earth software enables the user to view the earth's surface via satellite imagery. In most cases, this satellite imagery is high resolution (pixel size smaller than 5 m), as shown in the image of Harar in Figure 3d. The program is easy to use and with the time slider feature change in the landscape can be detected. The imagery on Google extends to 1945 in a limited number of areas (for example, London and Kent, UK) where reconnaissance aerial photography has been digitized and georeferenced; however, generally the datasets begin in 1984 (launch of Landsat 4–60 m resolution). Harar, Harlaa, and Nora have the most recent imagery, with Harar's last update in late 2017 and Harlaa and Nora's in early 2016. The most recent Sheikh Hussein imagery is of an unknown date as it is not displayed in the software, but there is earlier imagery from 2014. Google Earth data are not as complex as raw multispectral satellite imagery: although the image is derived from a high-resolution multispectral image, it has already been processed into a natural color image. Google Earth provides a standard RGB image of the earth that can be analyzed visually

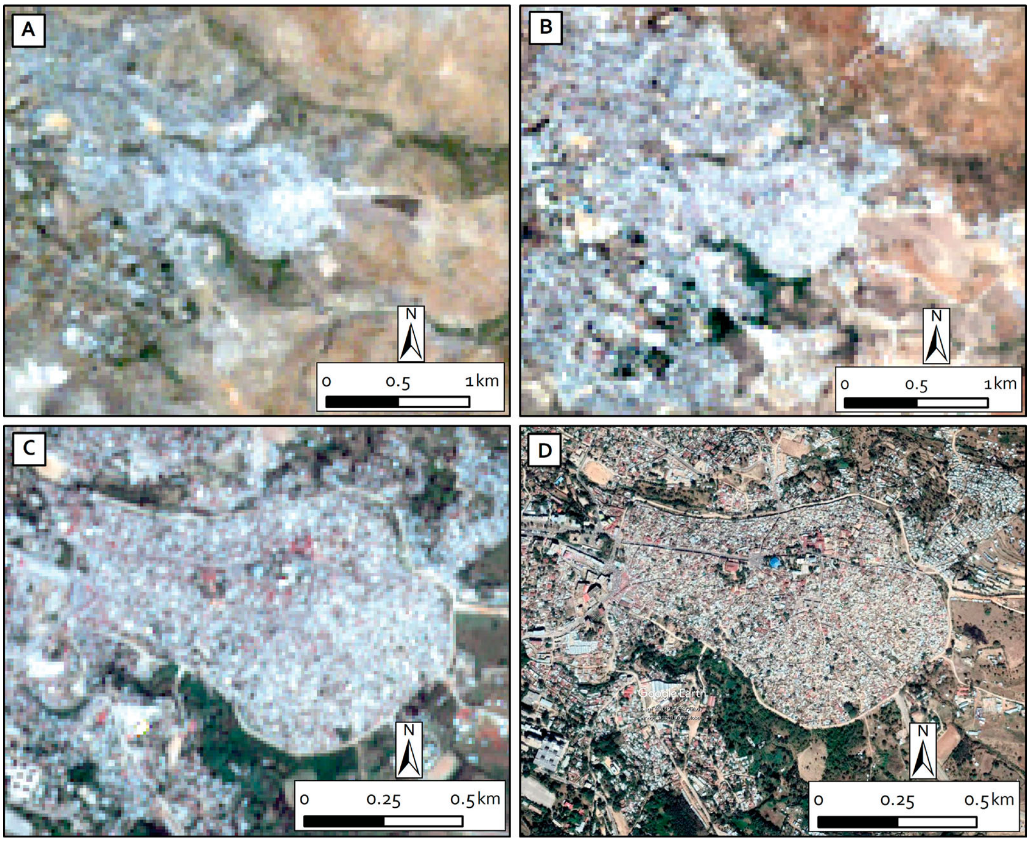

Figure 3. A) Landsat 5 TM image of Harar from February 20, 1996 (30 m resolution; bands 3, 2, and 1; image courtesy of NASA/USGS); B) Landsat 8 image of Harlaa and Harar from March 1, 2017 (bands 4, 3, 2; image courtesy of NASA/USGS.); C) Sentinel-2 imagery from February 10, 2018 (image courtesy of the ESA.); and D) Google Earth image December 10, 2018.

without any pre-processing. This type of data is useful as high-resolution satellite images are expensive to purchase, and large areas can be analyzed relatively quickly because no pre-processing is necessary. As of April 18, 2018, Google Earth was available via the Internet browser (https://earth.google.com), making imagery access easier. Google Earth Engine (https://earthengine.google.com/) is also now available and provides a catalogue of different satellite imagery, including historical imagery and geospatial datasets. Unlike Google Earth, it provides an Application Programming Interface (API) and other tools to enable the analysis of large datasets and allows for scientific analysis and visualization of other data.

Google Earth is a readily available tool for site identification if the imagery is available at a great enough resolution and the feature is detectable from the air. Moreover, if the site is already known (as they are in the examples here), then temporal imagery can be used to see how much the landscape has changed and to predict how it might change in the future.

Landsat 5 TM and 8 multispectral satellite imagery

Landsat multispectral satellite data covers a relatively broad time period (1989–2018). There are other examples of open access multispectral satellite data but they do not offer the same time frame. The Landsat Program, a joint NASA/USGS platform provides the longest continuous coverage of the earth's surface in existence. Images have been recorded daily since 1972, and are available from the United States Geological Survey (USGS) EarthExplorer website (https://earthexplorer.usgs.gov/). Landsat has several spectral bands depending on mission and a spatial resolution of 30 m per pixel. A multispectral sensor measures energy at different wavelengths of the electromagnetic spectrum creating a multilayer image, which goes beyond the red, green, and blue channels visible with the human eye. The first Landsat sensor in orbit captured four spectral bands: the visible green and red bands and two wavelengths of near-infrared (NIR) (NASA Landsat Science n.d.). The current Landsat sensor in orbit (Landsat 8) measures 11 multispectral bands (coastal/aerosol, blue, green, red, NIR, two short wavelength infrared, panchromatic cirrus, and two long wavelength infrared). Landsat imagery is medium resolution, meaning it does not have the spatial resolution suited to identifying sites from visual interpretation or automated approaches. However, the imagery gives a good overview of the topography and geomorphology of the landscape, as it can cover a large geographic area within one data tile; an example is provided in Figure 3a and b. The primary use of medium resolution imagery is to aid analysis and interpretation of the natural and built landscape.

The Landsat imagery used here consisted of multiple Landsat sensors over different time periods and was dependent on the suitability of the image. For example, an image with the least amount of cloud cover has to be used so the view from space is not obscured. A recurrent issue for image resolution for the four sites is that there was considerable cloud cover, making it difficult to see underlying topography in some tiles. The tiles listed in Table 1 have been chosen because they present the clearest coverage of each site, with minimal clouds present. Also, the time of year the imagery was captured is approximately the same for each site, meaning environmental factors such as vegetation cover and surface water should be similar.

Table 1. Metadata of the Landsat imagery obtained for the study areas.

Sensor	Image Date	Path	Row	Site
Landsat 8	01-03-2017	166	054	Harlaa/Harar
Landsat 5 TM	20-02-1996	166	054	Harlaa/Harar
Landsat 8	07-02-2018	167	055	Sheikh Hussein
Landsat 5 TM	23-02-1989	167	055	Sheikh Hussein
Landsat 8	26-11-2017	168	053	Nora
Landsat 5 TM	19-11-1991	168	053	Nora

Sentinel-2 imagery

Sentinel-2 imagery is from two sensors currently in orbit (Sentinel 2A and 2B) and is available from the USGS EarthExplorer website. The first sensor went into orbit on June 23, 2015 and the second on March 7, 2017. The main advantage of this imagery is the enhanced spatial resolution in comparison to Landsat, which is 10 m in the visible and NIR spectral bands; this difference can be seen by comparing the imagery in Figure 3c. This means any feature 10 m or more in size can be seen with the imagery. Furthermore, very up-to-date images are captured with these sensors and data are collected from the same location every five days.

Data pre-processing

All pre-processing of Landsat imagery was achieved in the software ERDAS Imagine 2016, which is widely available and used, including in Ethiopia itself (Tahir, Imam, and Hussain 2013). Level one data was downloaded, consisting of several files representing the different electromagnetic wavelengths of the image. First, a subset of the study area was taken from the separate layers to produce a smaller image (similar to cropping), then a process of image fusion was undertaken to join the multispectral bands together to create a color composite image. The standalone layers of the image are grayscale and the image only appears in color after the image fusion takes place. This image can be visualized in different ways, highlighting the topographic features of the landscape. For example, when the red, green, and blue bands are used, they will display "real" color as the eye sees it. This process was undertaken in ERDAS Imagine using the Layer Stack tool. This step is necessary for visualization and classification of the landscape, which can be more easily understood in color rather than grayscale.

The Landsat imagery was orthorectified using an open access digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) available from the USGS. Orthorectification removes any image distortions from the tilt of the satellite in orbit, which can cause some geometric errors. The final pre-processing is atmospheric correction. This correction is necessary as the energy captured by Landsat is influenced by the Earth's atmosphere and can be affected by gases, water vapor, and aerosols (Young et al. 2017). This calculates the spectral reflectance or data number (DN) for each pixel in the image which represents topography. Each pixel represents different phenomena on the ground.

Image classification

The classification process groups together pixels with the same spectral reflectance (i.e., the same topography). For

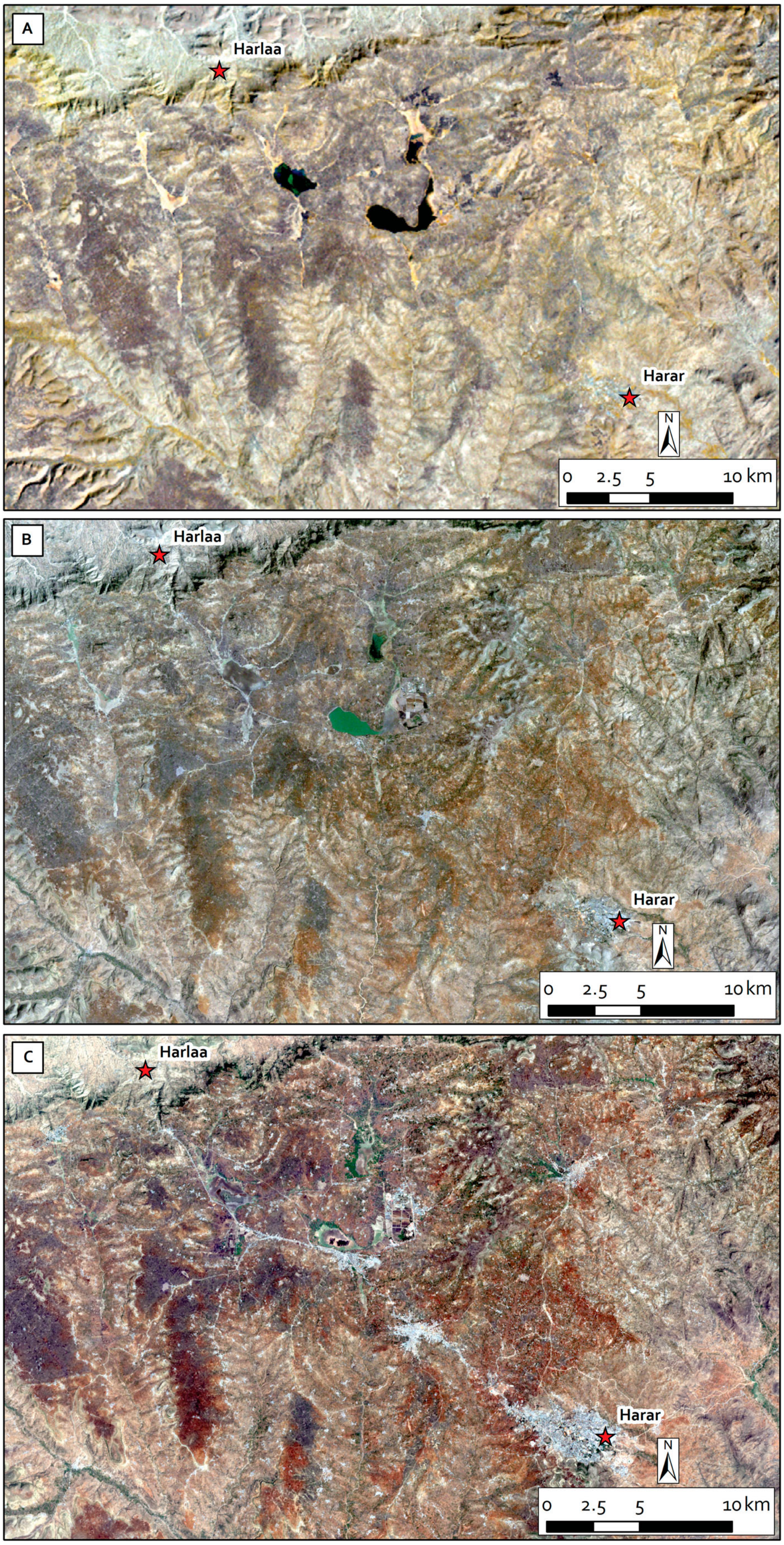

Figure 4. A) Landsat 5 MSS image of Harlaa and Harar from January 23, 1986 (60 m resolution; image courtesy of NASA/USGS); B) Landsat 5 TM image of Harlaa and Harar from February 20, 1996 (30 m resolution; image courtesy of NASA/USGS); and C) Landsat 8 image of Harlaa and Harar from March 1, 2017 (image courtesy of NASA/USGS).

example, all pixels where water is present on the land surface are represented in the image by the same pixel number. Classification functions in the software can calculate where the water pixels are throughout the image, then highlight them as the same color; similarly, vegetation of the same type will be represented in the same color, and urban areas

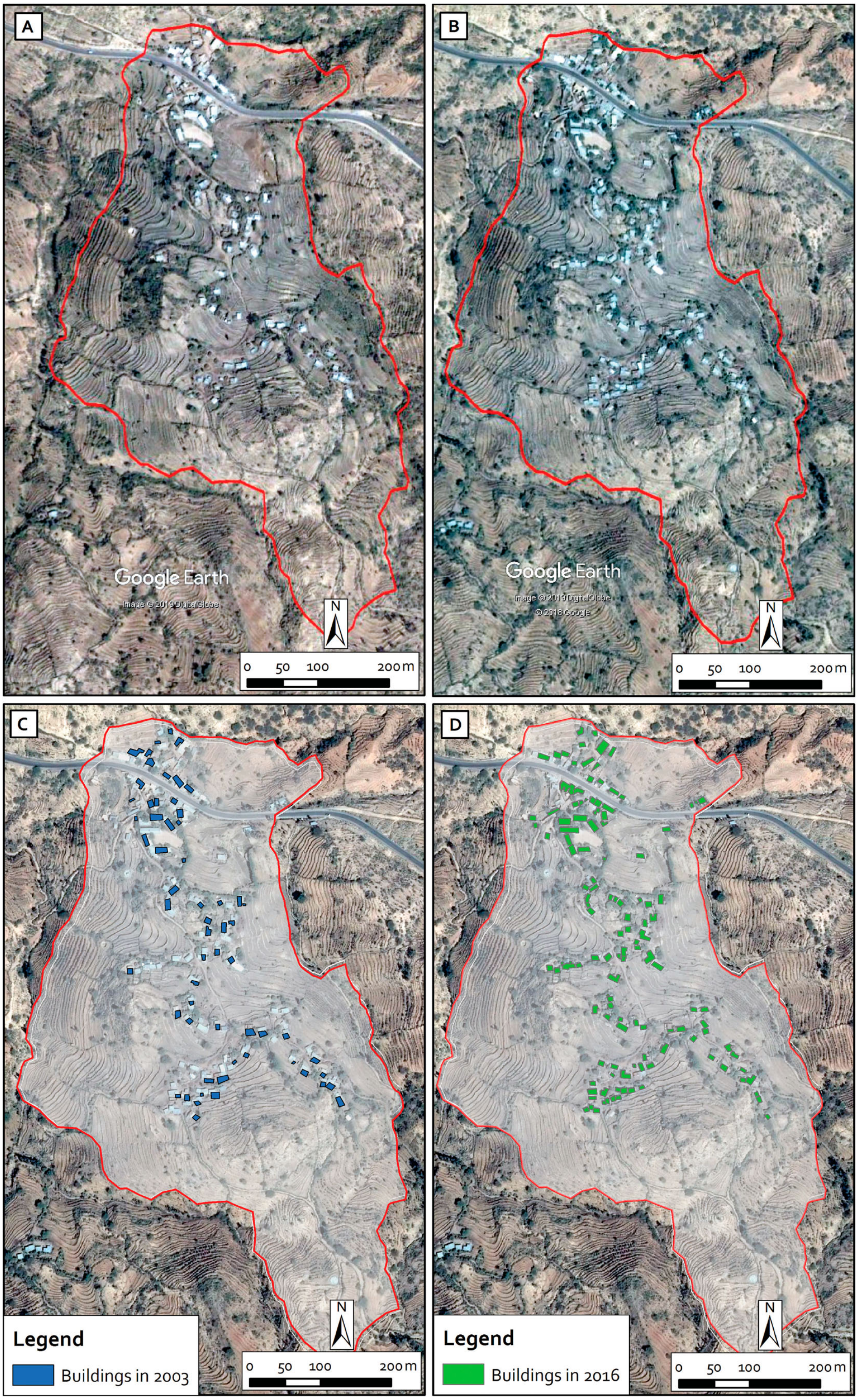

Figure 5. The boundary indicates the edges of Harlaa village, recorded during survey (Insoll et al. 2018). A) The Google Earth image shows Harlaa in February 2003; B) Harlaa in February 2016; C) a map based on Google Earth satellite imagery, GPS survey, and SRTM satellite data showing Harlaa in February 2003; and D) a map based on Google Earth satellite imagery, GPS survey, and SRTM satellite data showing Harlaa in February 2016. (Maps by Khalaf.)

another color, and so on. In order to detect change between different time periods in the same area, the software calculates how many more or less pixels of a particular land cover type are present in the images. For example, if a lake is represented by 50 pixels on an image in 1992, then in 2012 the same lake is represented by only 17 pixels, the software will show where the reduction in the lake has taken place. For the Ethiopian sites, vegetation, water, and urban sprawl were calculated in each image, then a change detection algorithm applied to see what had changed in the landscape.

Change detection

Detecting change in the landscape over time is an important aspect of this research. The technique of "change detection" is defined as a process of identifying and recording changes in the structure and use of the landscape by observing differences over time, and can be achieved using Landsat imagery (Howarth and Wickware 1981; Xian, Homer, and Fry 2009; Zhu and Woodcock 2014; Zhu 2017). This technique is a computational automated approach; it classifies the landscape in all images across a time frame, and then calculates the degree of change for each geomorphological and anthropogenic feature. However, it is can only capture features bigger than the 30 m pixel size of Landsat imagery.

Results

The results are presented by site. Three issues are considered: first, the suitability of the datasets for identifying and analyzing archaeological sites; second, the anthropogenic and environmental risk to the sites; and third, how the wider landscape can be illustrated with the remote sensing imagery.

Harlaa

The sites of Harlaa and Harar appear on the same Landsat tile (Figure 4). Three images were downloaded from the USGS website. At the top is a Landsat 5 MSS image from January 23, 1986 that shows the substantial change in the intervening landscape, particularly the lake, and was not used for analysis as the resolution is too low at 60 m per pixel. The middle image is Landsat 5 TM from February 20, 1996 and is one of the earliest images available with a resolution of 30 m per pixel. The Landsat 8 image at the bottom of Figure 4 is from March 1, 2017. Visual inspection of the images prior to classification presented in Figure 4 and particularly Figure 5, clearly shows the substantial difference in settlement size at Ganda Biyo (Harlaa) which has increased significantly over this time period.

Classification and counting of the buildings in Figure 5 substantiates the increase in settlement size. In February 2003, 61 modern buildings were identified in the village of Ganda Biyo/Harlaa. In February 2016, only 13 years later, the number had more than doubled to 127 modern buildings. There were also several buildings under construction when fieldwork was last completed in the area in February 2019. This process of settlement expansion is also evident in the Landsat imagery. Other elements that can be identified from comparison of the images in Figure 5 relate to differences in housing construction. In the earlier image from 2003 (Figure 5a), there is evidence of a traditional form of housing consisting of round, thatched houses, likely made of stone blocks mortared with earth. In the later image (Figure 5b), this type of house has disappeared completely and rectangular stone housing with corrugated iron roofing is only found.

To quantify urban change in the Harlaa/Harar area, the change detection method was performed on the Landsat images to analyze the difference in pixels between the images. Pixels that have had a more than 50% change are highlighted in green in Figure 6. This result is consistent with the visual inspection of the images, clearly showing the increase in building at and near both Harlaa and Harar. Change detection analysis has also highlighted areas that might have been missed using visual inspection.

Landscape terracing over the time scale analyzed in this paper has remained constant, with no significant increase evident through visual inspection of Google Earth imagery. However, there is now an increase in buildings within

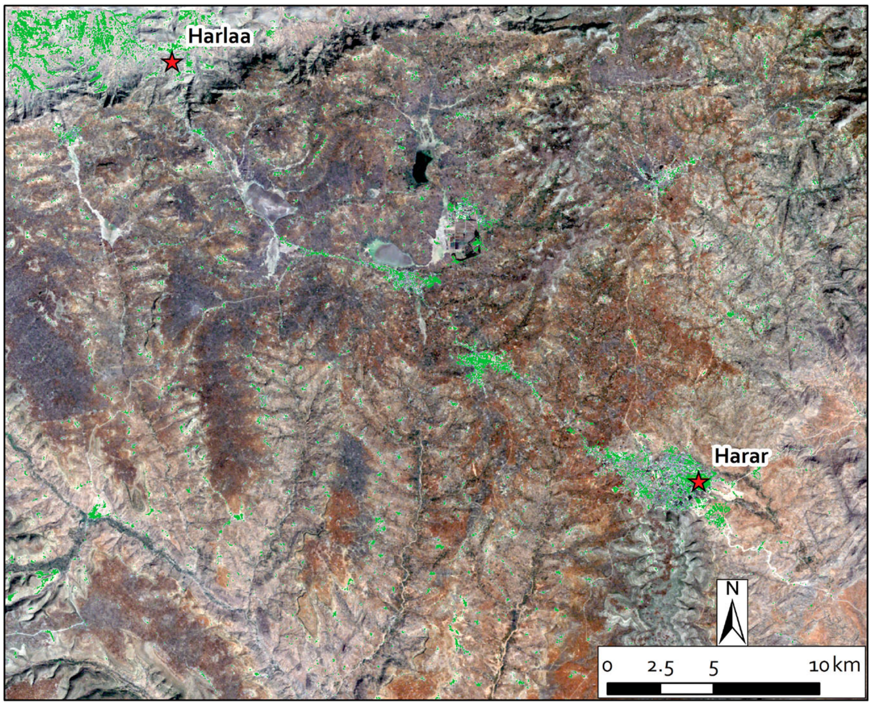

Figure 6. Green pixels show the extent of urban growth between 1996 and 2017. The satellite image is Landsat 5TM from 1996. (Image courtesy of NASA/USGS.)

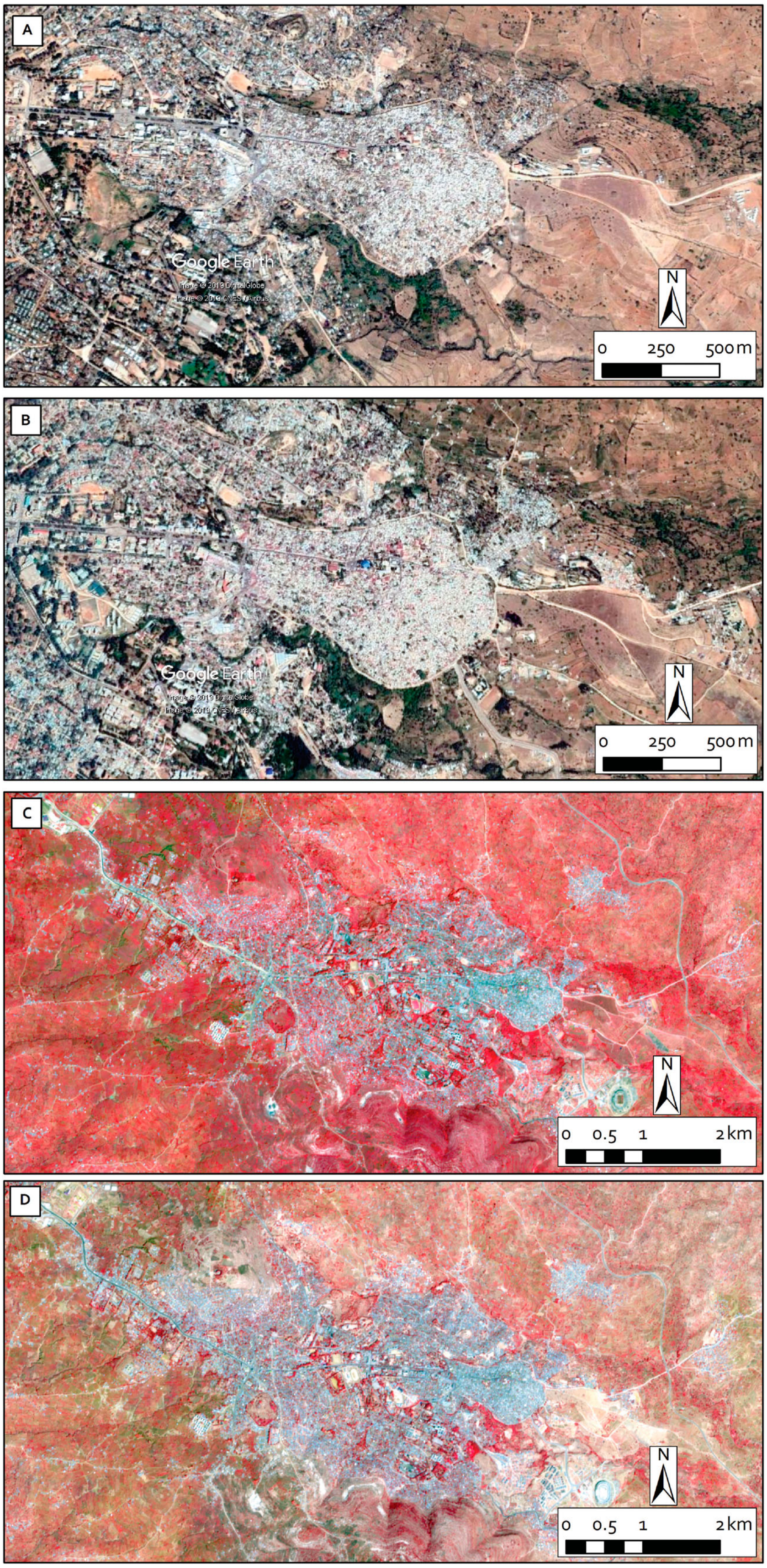

Figure 7. A) Google Earth image of Harar Djugel taken November 24, 2002. B) Google Earth Image of Harar taken December 10, 2018. Note the growth in urbanization outside the Djugel, particularly to the north-east. C) Sentinel-2 imagery showing NIR, red, and green bands highlighting urban features gray/lighter color. Vegetation is shown in red from October 28, 2016. D) Sentinel-2 from February 10, 2018. (Image courtesy of the ESA.)

terraced areas, reflecting the growth in population. Conversely, looting activity is not evident in the images as the resolution precludes identification of pits, unless of very large size.

Harar

The Landsat TM 5 images from 1986 and 1996 and the Landsat 8 image from 2017 provided in Figure 4 indicate the

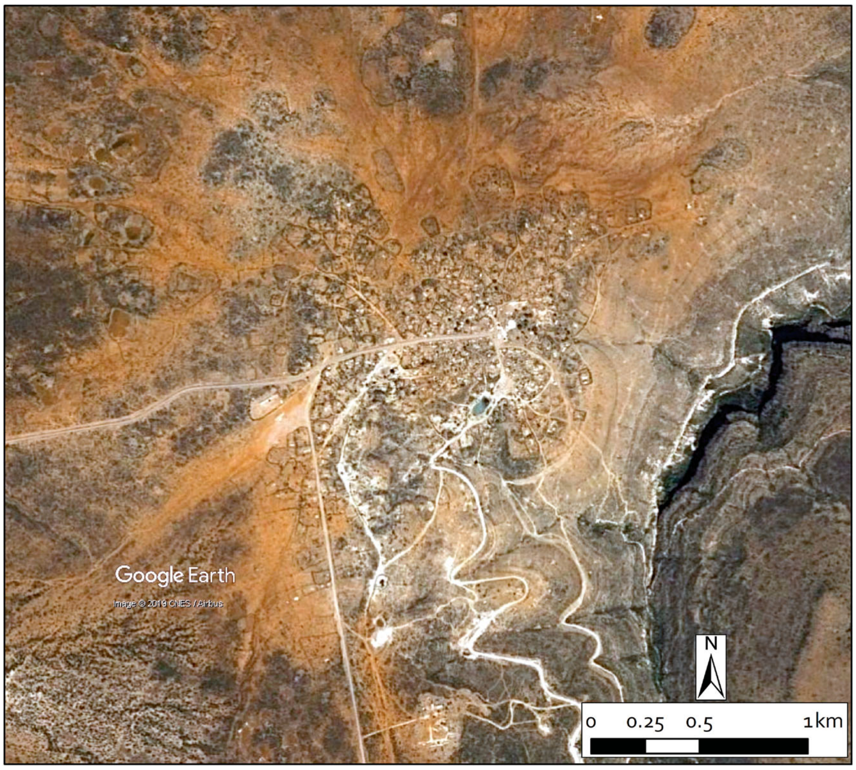

Figure 8. Google Earth imagery (date unknown) of Sheikh Hussein.

ribbon development that has occurred along the road between Harlaa and Harar, particularly at the roadside towns of Haramaya and Awaday. A related consequence of this urban expansion and population growth is the almost total disappearance of Lake Haramaya over the same period. It can be seen through comparing the images in Figure 4 that the lake has declined from approximately 4 km long by 1.5 km wide at its greatest extent, to a couple of small pools. Although archaeological survey of the region between Harlaa and Harar has not been completed, anthropogenic action attested by settlement development and environmental change is likely to have impacted on heritage.

Figure 7 illustrates how Harar has also grown substantially over the same time period with urban expansion in all directions. The suburbs of the new town were formerly concentrated to the west and north of the old city. Comparing the Google Earth imagery from 2002 and 2016 shows urban development east of the city. The east and northeast formed the historical approach route to Harar from the Red Sea ports, and it was from the east over the Erer River that, for example, Sir Richard Burton entered Harar in January 1855 (Burton 1987 [1894], 200–201). The exponential growth of the city to the east is primarily due to the construction of an area of diaspora housing to cater for the large Harari diaspora and the comparative prosperity they bring (Harari People Regional State Government Communications Affairs, n.d.).

Eastern expansion is likely to have impacted on the archaeology of the area, as it has impacted a natural/cultural heritage event that Harar is famous for: the nightly interaction through feeding of hyenas by the so-called "hyena men" (Briggs 2015, 453). Until approximately 2013, hyena feeding occurred adjacent to the djugel in the vicinity of the Aw Ansar Ahmed shrine; however, it has now been pushed approximately 3–4 km east by this urban expansion, and the numbers of hyenas appear to have reduced.

Not visible in the satellite images is a further correlate of urban expansion: the dumping of the city's rubbish between the djugel and the diaspora quarter. This phenomenon helps explain the absence of development in immediate proximity to the eastern djugel, which is the area with densest rubbish dumping recorded during survey (Insoll, Tesfaye, and Mahmoud 2014). As such, it functions as a buffer zone and the core area of the old city retains its integrity and has actually been enhanced by the clearing away of shanty and other house construction that abutted the northern side of the djugel wall. The building clearance is visible in the two images in the two Google Earth images in Figures 7a and b, where it is denoted by a sandy strip adjacent to the northern wall in the 2016 image, which is a new road built over the cleared houses as a buffer zone between the djugel and the suburbs of Harar. The rapidity of urbanization is further highlighted over an even shorter time frame in comparing the Sentinel-2 satellite imagery of Harar from 2016 and 2018 shown in Figures 7c and d.

Sheikh Hussein Shrine

Unlike Harlaa and Harar, Sheikh Hussein does not have clear resolution imagery on Google Earth (Figure 8). There are only two images available: one is from 2014 but has cloud cover, and the other is shown in Figure 8 but does not have the date displayed. Therefore, inferences about changes in the landscape cannot be made using Google Earth alone. The two Landsat images shown in Figures 9a and b, however, indicate some changes over the period between 1989 and 2018. The most obvious difference is the establishment of roads to the west and south of the town, making it more accessible. The town has also grown slightly in size to the north, but not to the extent evident at Harlaa and Harar. This difference could be the result of a variety of factors.

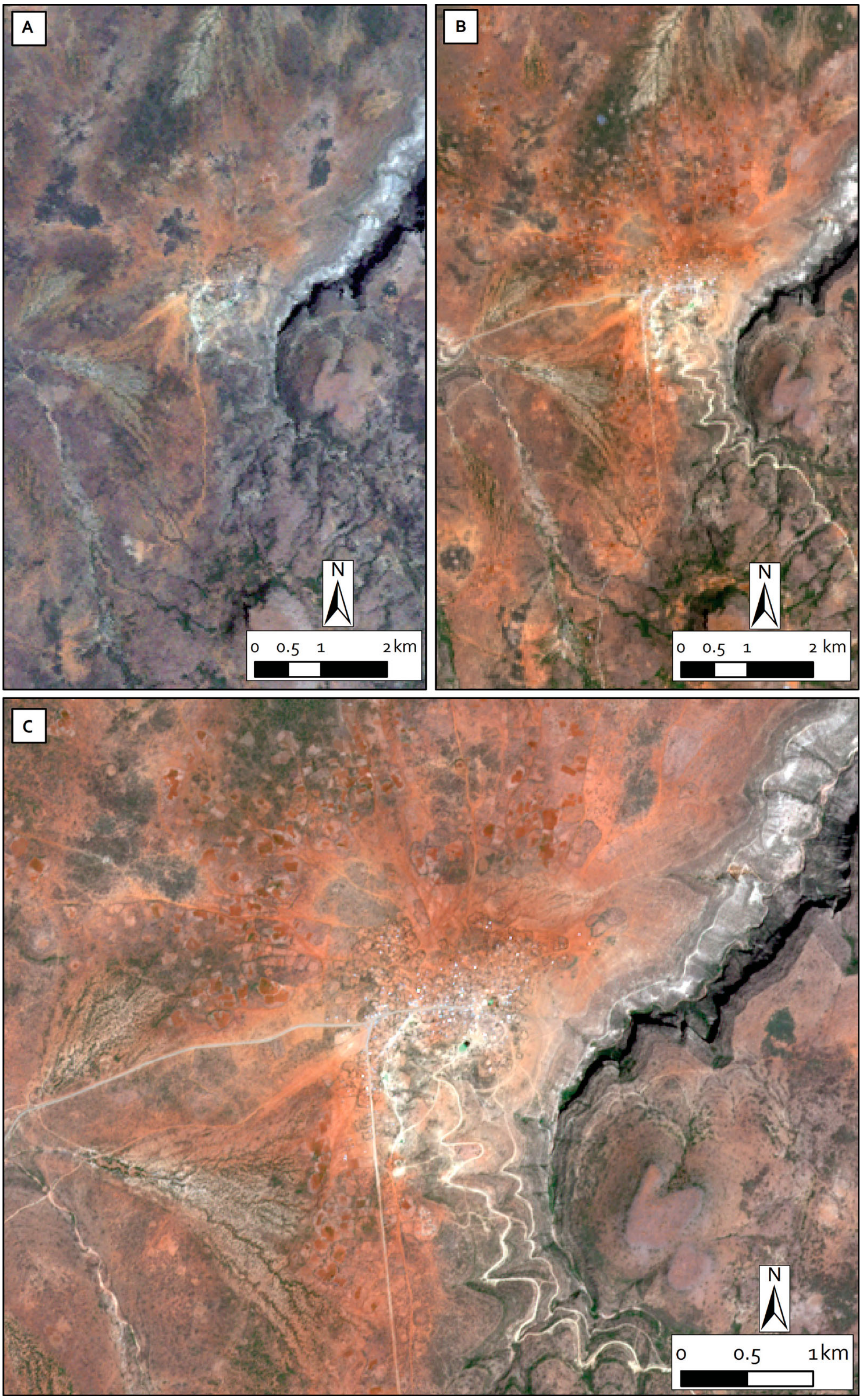

Figure 9. Satellite imagery showing the Sheikh Hussein in the center: A) natural color composite of Landsat 5 TM image (from February 23, 1989); B) Landsat 8 image from February 21, 2018 (natural color composite; image courtesy of NASA/USGS); and C) Sentinel-2 image from January 21, 2018 (image courtesy of ESA).

First, Sheikh Hussein is in an economically deprived area without proximity to a large city, unlike Harlaa. It also has little diasporic connection, and hence remittance income, in comparison to Harar. It is also little visited by tourists, though the Bale Mountains National Park to the south is the focus of trekking (Briggs 2015, 471–483).

Second, the absence of development at Sheikh Hussein probably also reflects recent change in local Islamic practice due to the increasing influence of Salafism (Østebø 2011, 2012). The decline in the importance of pilgrimage (*muuda*) to the site and increasing objections to deep-rooted indigenous practices such as making provision for

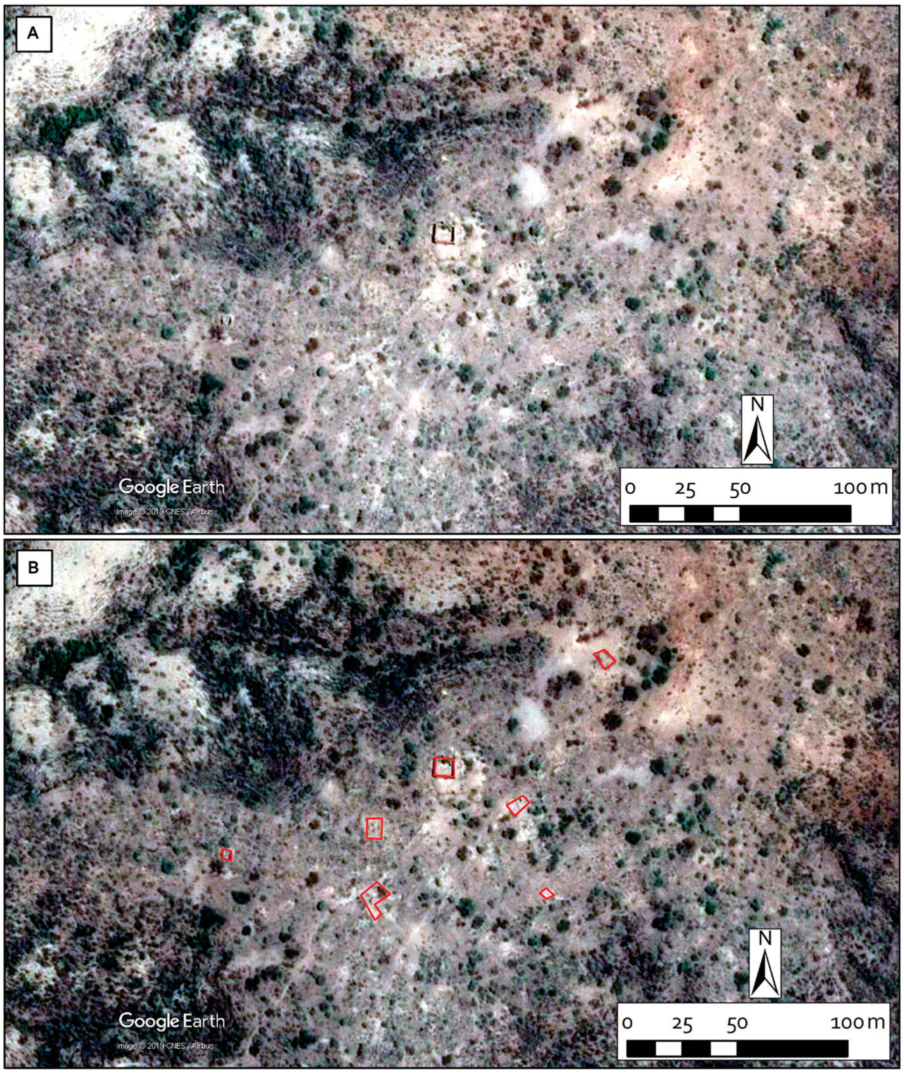

Figure 10. A) Google Earth image of the site of Nora, image taken March 15, 2016; and B) Google Earth image with red polygons indicating standing architecture at Nora.

a sacrifice (*wareega*) (Østebø 2011, 631–632) as "un-Islamic" are a feature of recent comments on the shrine (see, for example, Opride News [2011]). These are part of a larger shift in belief and practice, also attested among the local Oromo population in the diminution of elaborate tombs and grave visiting, as Salafist influence is increasing (Henze 2005, 191).

The absence of development also has positive connotations for the survival of heritage. The Sentinel-2 imagery from 2018 in Figure 9c indicates that Sheikh Hussein continues to be surrounded by areas of cultivation. Cultivation can be seen in the 2018 image to the north, and field boundaries can be demarcated, which are not as prominent in the 1989 image. The situation at Sheikh Hussein is in contrast to Harar, where formerly agricultural land is rapidly being used for building; however an increase in agriculture, if unmonitored, could also affect sub-surface archaeology.

It is also possible that erosion, linked with deforestation in the Bale region, has been a factor in influencing the landscape surrounding Sheikh Hussein in the past two decades. Soil erosion could have potentially affected archaeological sites in the region but this requires ground survey and an inventory of sites is still uncompleted for this area. An analysis of Sentinel-2 imagery of the area over a longer time frame will indicate whether erosion is a factor, however the currently available time depth for this imagery is not great enough to provide such an assessment.

Nora

Nora appears to be the least impacted of the sites. However, future threats could result from increased access to the area as a consequence of the new Awash-Kombolcha-Hara Gebaya Railway Project that is being constructed by Yapi Merkezi Construction Industry ca. 3 km northwest of the site (Awash-Hara Gebeya Railway Project n.d.).

The standing architecture at Nora can be clearly seen from Google Earth shown in Figure 10a. The site appears isolated within its immediate surroundings, in comparison to the other urban sites considered where the archaeology is not obvious in the satellite data. Thus, a relatively accurate sketch map can be prepared from the remote sensing imagery of this type of site, as illustrated in Figure 10b, which saves time in the field and can allow identification of features that may not be obvious on the ground.

The Landsat imagery shows landscape change over time. In the 1991 image (FIGURE 11A) the landscape appears relatively sparsely used, with an area of cultivation to the north of the site and little evidence of urbanization visible at this resolution. Twenty-two years later, the situation has changed

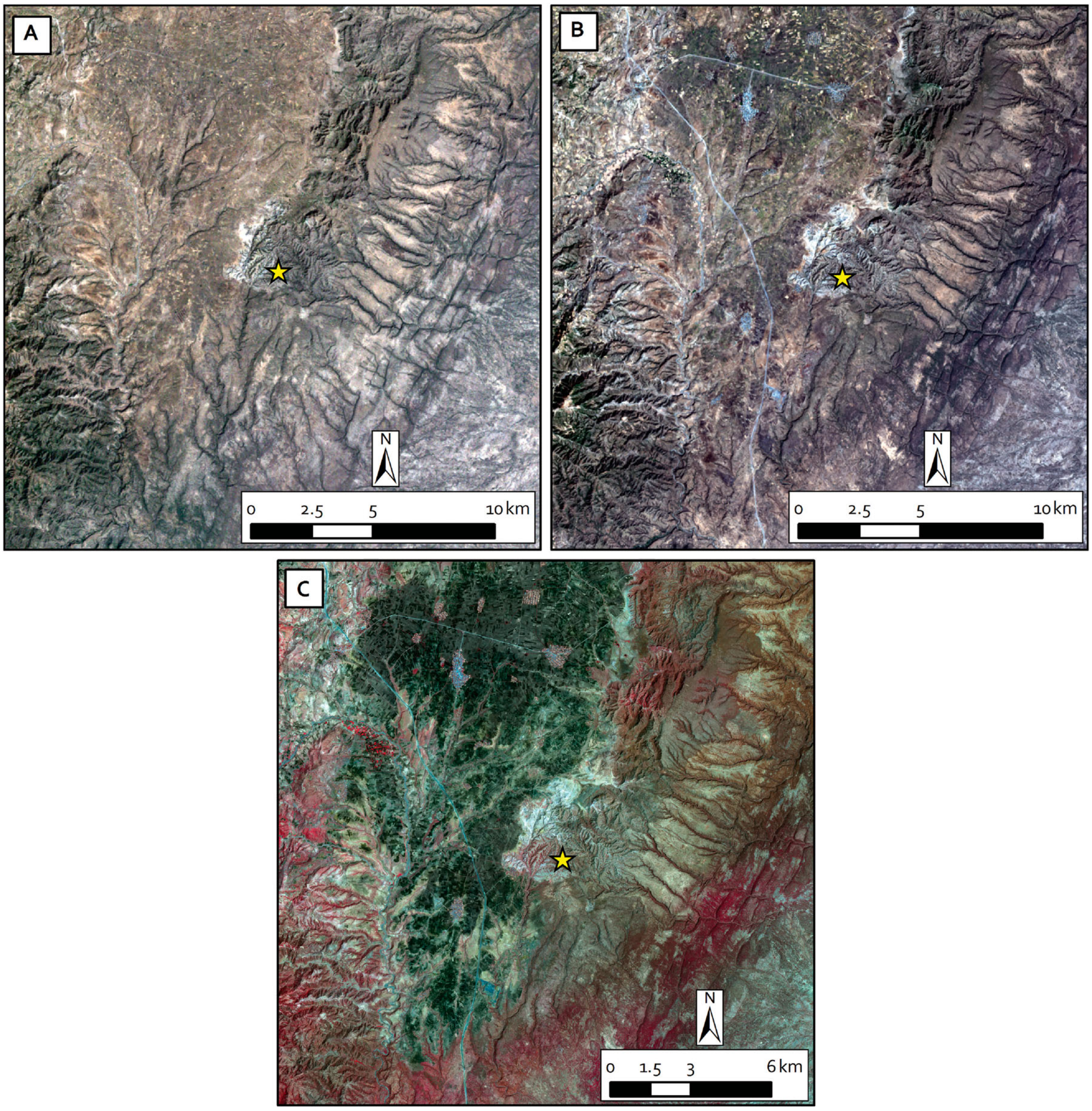

Figure 11. Satellite imagery of the site Nora, indicated by the yellow triangle. A) Landsat 5 image taken on November 19, 1991 (bands 3, 2, and 1; image courtesy of NASA/USGS); B) Landsat 8 image taken November 26, 2017 (bands 4, 3, and 2); and C) Sentinel-2 image taken on March 10, 2018 (bands 4, 3, and 2; image courtesy of ESA).

with the rail network a significant feature, as seen in greater detail at a higher resolution on the Sentinel-2 image (FIGURE 11C). There are also small clusters of villages that appear to be developing close to the railway, likely attracted by easier access to goods and services. Surrounding these villages is an increasing intensity of cultivated land. Rectangular field systems can be seen to the north and west of the site in the 2017 Landsat image in Figure 11b, and field system growth is visible in comparing the two images from 1991 and 2017 (FIGURES 11A and B). Meanwhile, in the southwest of the 2017 image, a prominent settlement has appeared, which was barely noticeable in 1991.

Discussion

It is evident that open access satellite imagery is a useful tool for monitoring archaeological sites over different time periods in the Ethiopian context, where ground accessibility could be limited for reasons of cost or local restrictions. However, as has been established, open access multispectral satellite remote sensing data does not offer a solution for site identification. The resolution is too low to generally allow recognition of archaeological features without prior knowledge of their existence, as with the four case studies here, all of which were archaeologically known, albeit to varying degrees. We need open access imagery, but it also has to be of high quality and adequate resolution to be effective. Open access satellite imagery also needs to be used in conjunction, where possible, with the collection "of ground-truth continuous data" (Dana Negula et al. 2015, 444). If the exact location of the site is already known, the general landscape surrounding it can be monitored for change.

There are both pros and cons to using medium resolution satellite imagery, such as Landsat and Sentinel-2, for archaeological research, as already discussed, but this study has shown that the benefits far outweigh the disadvantages. First, landscape mapping using open access imagery is less time consuming than obtaining a large-scale map (which in African contexts can be difficult) or conducting field survey. In Ethiopia, for example, the highest resolution maps available are the 1:50,000 series ETH-4, though a 1:10,000 series is currently under preparation by the Ethiopian Geo-Spatial

Information Agency (M. Gebremikael, personal communication 2018). Second, a very large area can be covered as soon as the imagery is downloaded.

As has been shown, the results of the remote sensing data analysis can indicate the impacts of settlement expansion upon the archaeological landscape (Harlaa and Harar), the need for conservation measures (Harar), increase in agricultural activity (Sheikh Hussein; Nora), and current site stability, as well as potential future infrastructure impacts (Nora) and environmental change (Harlaa and Harar). Interpretation of this imagery must also draw upon the wider social and economic context, as was apparent in Harar with the diaspora factor or the changes in Islamic practice at Sheikh Hussein.

Future research on remote sensing in archaeological contexts in Ethiopia could be extended to different environmental zones outside the remit of the "Becoming Muslim" project, where there were historically known Muslim populations. For instance, the arid areas of the Ogaden with their Somali pastoralist inhabitants or the Afar depression would be useful case studies. Other areas could include the more heavily forested zones of Kaffa, and to a lesser extent Jimma, where there have been Muslim populations established since at least the 19th century (Trimingham 1968, 29).

Conclusions

Open access satellite remote sensing imagery offers a mechanism for evaluating site status and conservation over time at a large scale. It permits a view of potential dangers facing known sites such as Nora, Harlaa, Harar, and Sheikh Hussein, rather than permitting the discovery of new sites (though this can occur). It is a first choice and effective tool for site monitoring but does not provide an alternative to field survey. This imagery is particularly useful for assessing general trends in relation to landscape alteration and settlement expansion and can be used remotely by desk officers in heritage bodies where internet links and computer accessibility permit it, to instruct field officers where these facilities are more limited. In the Ethiopian context the value of open access remote sensing and GIS for the monitoring of archaeological sites has been promoted by the authors through training courses run at the Headquarters of the Federal Government body charged with heritage protection, the Authority for Research and Conservation of Cultural Heritage in Addis Ababa. The second stage is involving training Headquarters staff to maintain communication with the Cultural Bureau offices in, for example Harar and Dire Dawa and, in turn, to the local district (*kebele*) officials, where direct access to this data is more limited, or impossible.

Remote sensing data can also be used to augment the integrated World Heritage database being developed by UNESCO (Dana Negula et al. 2015, 440), and as an adjunct to UNESCO monitoring of cultural heritage sites under threat (UNESCO World Heritage Centre 2016). Overall, the prospects for the utility of open access satellite remote sensing imagery as a heritage management tool in Ethiopia will increase as the bank of available images expands and as their resolution improves as new satellites are brought into service. We hope that similar initiatives will be developed elsewhere in Africa, particularly south of the Sahara.

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