



# Archaeology in the Fourth Dimension: Studying Landscapes with Multitemporal PlanetScope Satellite Data

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## Abstract

For the last seven years, PlanetScope satellites have started near-daily imaging of parts of the Earth's surface, making high-density multitemporal, multispectral, 3-m pixel imagery accessible to researchers. Multitemporal satellite data enables landscape archaeologists to examine changes in environmental conditions at time scales ranging from daily to decadal. This kind of temporal resolution can accentuate landscape features on the ground by de-emphasizing non-permanent signatures caused by seasonal or even daily changes in vegetation. We argue that the availability of high spatial and temporal resolution multispectral imagery from Planet Inc. will enable new approaches to studying archaeological visibility in landscapes. While palimpsests are discrete overlapping layers of material accumulation, multitemporal composites capture cyclical and seasonal time and can be used to interpret past landscape histories at multiple scales. To illustrate this perspective, we present three case studies using PlanetScope imagery in tropical environments on the Indian Ocean islands of Madagascar, Mauritius, and Zanzibar.

**Keywords** Multitemporal resolution · Satellite remote sensing · Landscape archaeology · Socioecological systems · Indian Ocean · Africa

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## Introduction

In this paper, we demonstrate how remote sensing approaches can be used to explore multiple scales of human behavior and contribute to a deeper theoretical understanding of socioecological (*sensu* Fitzhugh *et al.*, 2019) landscapes. Advances in satellite remote sensing have drastically reduced the revisit time of satellites to specific locations around the world. Some satellites now capture imagery on daily cycles, producing “multitemporal” datasets that enable new scales of landscape observation and analysis. Such multitemporal analysis can enable researchers to examine incremental landscape changes and provide new insights about how societies have altered their environments in response to social, environmental, and political events.

With the advent of satellites with high temporal resolution and nearly ubiquitous geographic coverage, archaeologists now have the capacity to examine landscapes across periods of time ranging from several days to several decades. The frequency of image capture (temporal resolution) has increased over time while costs of downloadable data have decreased, making multitemporal datasets more accessible than ever. Some of the first archaeological case studies using multitemporal satellite data drew on images from the long-running Landsat program, which began in the 1970s (*e.g.*, Custer *et al.*, 1986; Dorsett *et al.*, 1984; Findlow & Confeld, 1980; Richards, 1989). More recently, archaeologists have used the European Space Agency’s Sentinel program, offering multispectral datasets at 10–60 m resolution and a revisit cycle of 5 days (*e.g.*, Abate *et al.*, 2020). Planet Inc.’s PlanetScope configuration promises even better spatial and temporal resolution (though slightly less spectral resolution—Landsat and Sentinel have 11 and 13 bands, respectively, while PlanetScope has 8) and has the potential to transform archaeological remote sensing by providing nearly daily multispectral coverage of most parts of the Earth’s surface at 3 m spatial resolution. At the time of publication, the service offers researchers up to 5000 square kilometers of imagery each year at no cost. These high-density datasets provide an opportunity to rethink archaeological approaches to landscapes.

Archaeologists have long sought to model intensive and extensive land use, water management, and the trajectories of urban and rural settlement. The earliest attempts to investigate hydrological and agricultural systems involved intensive field surveys (*e.g.*, Adams, 1965), but remote sensing technologies have also expedited the process of detecting and quantifying landscape features, predominately through high spatial and multispectral data. Some methods for modeling and quantifying field systems include uses of aerial imagery and declassified mid-century satellite imagery to view now destroyed agricultural landscapes (Casana, 2020; McLeester & Casana, 2021); uses of LiDAR to detect field walls, terraces, and other features (Comer *et al.*, 2019; Küçükdemirci *et al.*, 2022; Ladefoged *et al.*, 2011; McCoy *et al.*, 2011); hydrological modeling to investigate water management strategies (Bruins *et al.*, 2019; Harrower, 2009, 2010); and UAV mapping to identify agricultural features at a high spatial resolution (Rouse *et al.*, 2021). Other archaeologists have used multispectral imagery to understand contemporary vegetation land cover in relation to archaeological sites and features (*e.g.*, Biagetti *et al.*, 2017; Reid, 2020; Vining & Williams, 2020).

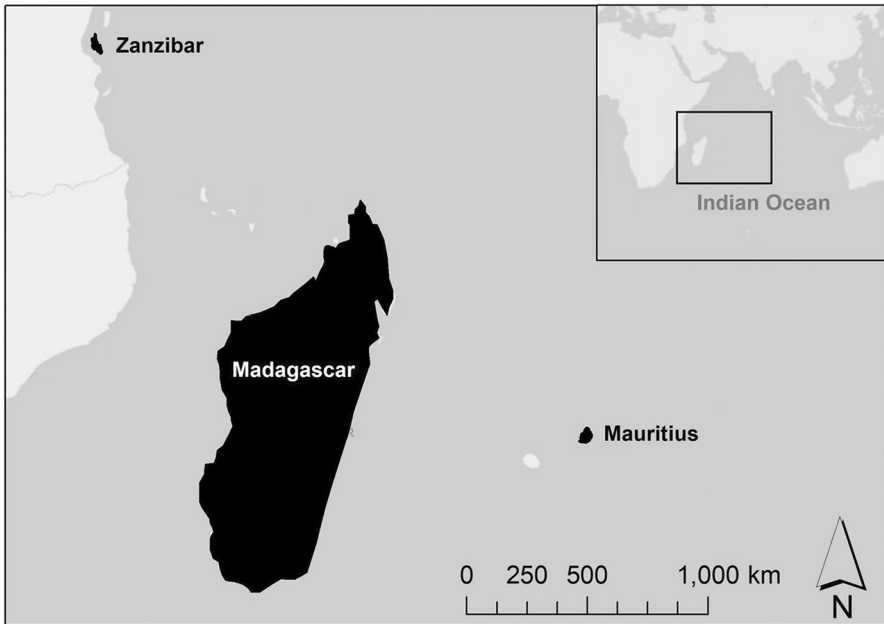
When thinking about change over time, landscape archaeologists have mobilized the concept of palimpsests (*e.g.*, Randall, 1934; Crawford, 1953; Bailey, 1981).

A landscape palimpsest refers to an area where the accumulated effects of human activities have successively deposited materials that become differentially compressed, reworked, and mixed (Bailey, 2007). Accreted materials across palimpsest landscapes may also shape the present and future patterns of land use, constraining future trajectories (see Bauer & Kosiba, 2016; Ingold, 1993; Morrison, 2013). Recognizing the palimpsest nature of landscapes, therefore, directs archaeologists toward understanding contemporary patterns in land use built out of past accretions. But representing a landscape as a palimpsest fundamentally involves a reduction, as temporally non-discrete events that produce features are simplified into discrete objects. Cumulative palimpsests are "...characterized not so much by loss of material but by loss of resolution" (Bailey, 2007: 204). Traditional geospatial approaches to landscape palimpsests use the layered nature of a geographic information system (GIS) to represent accumulated materials across a region, emphasizing spatial relationships between features and denoting chronological differences through notation and symbology. This type of representation remains a fundamental part of archaeological exploratory data analysis.

As Johnson & Ouimet (2018) have argued, geospatial data like LiDAR may be used to study landscapes as palimpsests, revealing the overlapping traces of past human activity. Multitemporal satellite data may also enable the reconstruction of temporal elements in a landscape in an alternative way, through the creation of seasonal composites to capture a spectrum of cyclical landscape alterations. This shifts focus from landscapes as static palimpsests toward a view of human eco-dynamics and landscapes as emergent, complex socioecological systems (see Davis, 2023; Fitzhugh *et al.*, 2019; Lansing, 2003; Mitchell, 2009; Preiser *et al.*, 2018), enriching the landscape palimpsest concept. These perspectives allow us to document the multi-scalar and cross-scalar interactions between environmental and sociocultural systems that characterize landscapes in the past and present.

In this paper, we present three examples of how multitemporal resolution satellite data from PlanetScope satellites can impact the way that archaeologists view landscapes. Drawing on case studies from Madagascar, Zanzibar, and Mauritius (Fig. 1), we argue that seasonal composites from multitemporal data enable a reconstruction of landscapes as complex, emergent systems, rather than as palimpsests of discrete objects arrayed in spatial juxtaposition. In Madagascar, Normalized Difference Vegetation Index (NDVI) reflectance values derived from seasonal composites are used to demonstrate long-term impacts of small-scale fisher-foragers on landscape and ecosystem stability. In Zanzibar, Tanzania, seasonal imagery analysis revealed the full extent of swidden field landscape changes in the areas surrounding a historic Swahili village of the early colonial period. Finally, in Mauritius, a multiple season composite enabled the extraction of field boundaries for a modern sugar cane field system, enabling comparisons with historical plantation boundaries.

All three case studies demonstrate the potential of newly available satellite imagery in the tropics, a region of the world where aerial photographs and optical imagery in general have been less useful for archaeological prospection than other more arid regions because of heavier vegetation cover (Casana, 2021: 172). While similar in environment and region, we chose these different case studies to demonstrate the utility of multitemporal methods for understanding emergent



**Fig. 1** Location of the three case studies (from left to right: Zanzibar, Madagascar, and Mauritius) within the Western Indian Ocean

socioecological systems in diverse social contexts and at different scales. The Madagascar case study reflects semi-mobile fisher-hunter-gatherer impacts on landscapes, the Zanzibar case study investigates root crop and banana agriculture in small-scale subsistence swidden field plots, and the Mauritius example demonstrates the socioecological impacts of colonial monocropping. All three case studies make methodological contributions that may help archaeologists rapidly and accurately delineate and quantify the extent of ancient and historical land-use systems globally.

## Applications of Multitemporal Satellite Imagery in Archaeology

Remote sensing has become an integral component for investigating archaeological landscapes (Casana, 2021; Opitz & Hermann, 2018). High-density survey and measurement technologies are transforming spatial archaeology (Opitz & Limp, 2015), constituting what McCoy (2021) has termed a geospatial revolution. As satellite imagery has become more available and of higher quality in terms of resolution, archaeologists have found ways to combine images of the same landscape at different points in time to reduce noise caused by seasonal variations in vegetation, soil, and cloud cover. This involves multi-temporal data wherein sensors repeatedly capture the same area on a daily, weekly, or monthly basis. Image quality is also measured in terms of spatial resolution (the area on the ground covered by a single pixel), spectral resolution (the number of wavelengths of light captured by a sensor), and radiometric resolution (the intensity of electromagnetic

energy captured within a pixel, represented as bits). High spatial resolution still remains the paramount factor for most archaeologists when it comes to deciding whether acquiring satellite imagery will be worthwhile. Exploratory visual inspection of high-spatial-resolution imagery has become an integral, commonplace aspect of most modern field projects since free and user-friendly search engines like Google Maps and Google Earth make viewing and browsing satellite imagery of a survey region or field site highly accessible. Satellite imagery with higher spectral resolution (multi- and hyper-spectral) has similarly become increasingly desirable as applications for its use have developed in recent years (e.g., Agapiou *et al.*, 2014; Aqduş *et al.*, 2012; Klehm *et al.*, 2019; Reid, 2020; Thabeng *et al.*, 2019; Vining & Williams, 2020).

In contrast, applications of high-temporal resolution imagery remain underdeveloped since using these datasets requires a greater degree of investment in processing. This is due to the need to manage more data compared to analyses that only rely on an image composite from a single time period. Some examples, however, include landscape reconstruction through a “time-series” approach, which compares images of the same place at different points in time over multiple decades. In this way, archaeologists can glimpse past landscapes prior to development, like well-known studies using CORONA and HEXAGON imagery (Casana, 2020; Elfadaly *et al.*, 2023; Hammer *et al.*, 2022; Menze & Ur, 2012). Though these imagery sources remain behind paywalls, they have become free to download and use for some regions, through projects like the Corona Atlas (Corona Atlas, 2024). Archaeologists have also recently combined multitemporal data with machine learning and deep learning algorithms to detect archaeological mounds across vast areas (Berganzo-Besga *et al.*, 2021; Orenco *et al.*, 2020). Others have used satellite and drone multispectral imagery with high temporal resolution to investigate crop marks as proxies for archaeological sites (Abate *et al.*, 2020; Hill *et al.*, 2020; Moriarty *et al.*, 2018). Finally, another application of multitemporal satellite data is for monitoring site damage and looting, allowing an analysis of changes to heritage landscapes over time (Parcak *et al.*, 2016; Rayne *et al.*, 2020; Tapete & Cigna, 2019).

While its recent development limits its current utility for decadal comparison, PlanetScope appears poised to become the most important source of multitemporal satellite data for archaeologists. It eclipses Sentinel-2 and Landsat 8 imagery in spatial and temporal resolution while still featuring multispectral capabilities (see Tables 1 and 2).

**Table 1** PlanetScope Dove satellite array, multispectral bands, and wavelengths. From the PlanetScope website

Band	Wavelength	PlanetScope Dove-C (4 band, 2017–2021)	PlanetScope Dove-R (8-band, since 2021)
Coastal Blue	431–452 nm		X
Blue	465–515 nm	X	X
Green I	513–549 nm		X
Green	547–583 nm	X	X
Yellow	600–680 nm		X
Red	650–680 nm	X	X
Red-Edge	697–713 nm		X
NIR	845–885 nm	X	X

**Table 2** Comparing spatial, spectral, and temporal resolution of Planet, Sentinel-2, and Landsat 8

Sensor	Spatial resolution	Spectral resolution	Temporal resolution
PlanetScope Dove-C	3 m	4 bands	Daily revisitation since 2017
PlanetScope Dove-R	3 m	8 bands	Daily revisitation since 2021
Landsat 8	30 m multispectral, 15-m panchromatic	11 bands	16-day revisitation cycle since 2013
Sentinel-2	10 m (4 bands), 20 m (6 bands), 60 m (3 bands)	13 bands	5-day revisitation since 2015

PlanetScope's 430+ Dove satellites have been collecting 4-band multispectral imagery since 2017, and since August 2021, sensors have begun to operate in eight bands on a daily basis (see Table 1). Archaeologists have begun to apply PlanetScope datasets alongside other remote sensing sources to inform archaeological field surveys (Plekhov *et al.*, 2020), reconstruct ancient sites and landscapes (Davis & Douglass, 2021; Hegyi *et al.*, 2020), and monitor cultural heritage (Conesa *et al.*, 2023; McGrath *et al.*, 2022; Plekhov & Levine, 2018; Titolo, 2021). While these studies point to the emerging utility of PlanetScope imagery, they also highlight that a limitation is the data's availability; compared to Sentinel and Landsat which are free to use, PlanetScope data remains pay-walled. However, at the time of publication, Planet Inc. makes free academic licenses available to researchers and students, granting 5000 sq. km of free imagery per month as part of Planet's Education and Research Program.

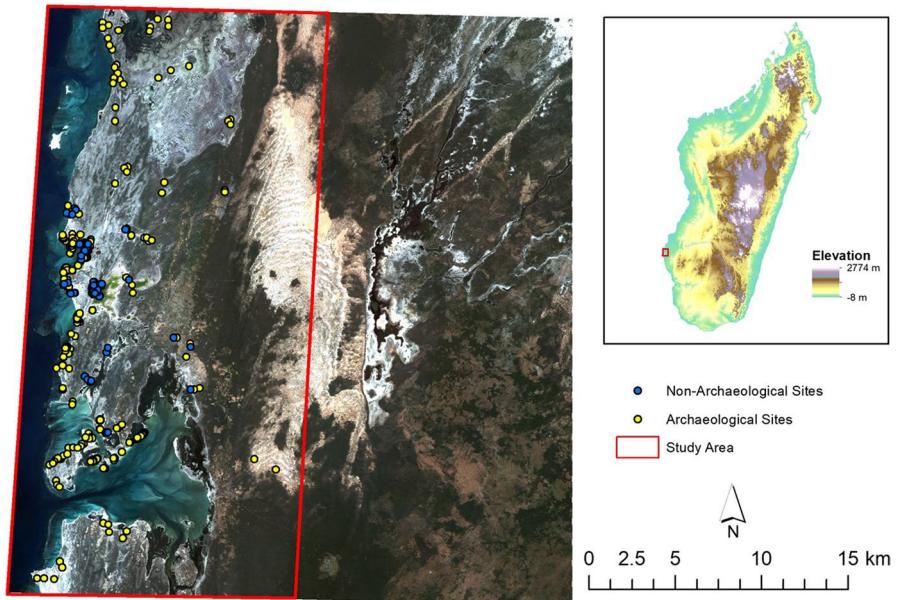
To test the applicability of multitemporal PlanetScope data for understanding socio-ecological landscape change, we developed three case studies for islands in the western Indian Ocean. Given their natural oceanic boundaries and constrained occupation histories, islands are uniquely suited for investigating long-term human impacts on environments (Kirch, 2007). Mitchell (2022) also emphasizes the potential for the archaeology of African islands in particular to elucidate how humans have transformed landscapes through intentional or accidental interventions. Island archaeologists in particular have leveraged the framework of human eco-dynamics to characterize human–environment interactions (Braje *et al.*, 2017; Faulkner *et al.*, 2022; Fitzhugh *et al.*, 2019; Kirch, 2007). As such, island environments are pivotal for testing the applicability of newly available multitemporal PlanetScope imagery for archaeological questions about landscape change. Since 2017, PlanetScope satellite configurations have captured images of islands in the western Indian Ocean on a near-daily basis, providing large quantities of high-resolution cloud-free multitemporal imagery of this region. These new datasets are useful for archaeologists and earth scientists interested in the role of human activities within landscapes and ecological systems that can be traced through patterns of land-use change (Ellis *et al.*, 2021; Stephens *et al.*, 2019). Using a dataset from a single time period only affords researchers the ability to evaluate the current state of a system, but not how that system's state changes across time periods. PlanetScope multitemporal data, in contrast, enables a consideration of the emergent landscapes that humans produced in African islands as they settled new regions, transformed environments, developed complex societies, and resisted colonization.

**Fig. 2** Example of an open-air archaeological site (G134) in SW Madagascar. Surface deposits consist of ceramic sherds, modified marine shell tools, and other ephemeral traces of human activity. Photo taken by George Manahira



## Multitemporal Analysis and the Study of Mobile Foraging Community Resilience on SW Madagascar

Madagascar represents a unique case study of how multitemporal remote sensing can illuminate important insights into mobile foraging communities and their impact on landscapes. The island is the fourth largest in the world, by area, and contains an extensive archaeological record spanning at least the past two millennia (Dewar & Wright, 1993; Douglass *et al.*, 2019). In the southwest of the island, the preservation



**Fig. 3** Map of study area located in the Velondriake Marine Protected Area in southwest Madagascar

of cultural materials can be an issue. The archaeological record consists of mostly artifact scatters which represent ephemeral traces of mobile campsites and (semi)sedentary villages (Fig. 2). Within the Velondriake region of SW Madagascar (Fig. 3), communities primarily identify as *Vezo*, an identity centered on maritime livelihoods (Astuti, 1995; Iida, 2005). The area has been inhabited for millennia by foraging and fishing communities, and over the past several centuries, additional subsistence practices like agropastoralism have been introduced (Douglass *et al.*, 2018; Hixon *et al.*, 2021). Within the southwest, there are two distinct seasons: a wet season (with monsoon-like conditions) lasting from November to April, and a dry season with less than 50 cm of annual rainfall (Douglass & Zinke, 2015) from May to October.

Because of their subtle nature, identifying signatures of archaeological deposits through remote sensing requires high spatial, spectral, and temporal resolution to identify faint differences in geophysical characteristics (Davis & Douglass, 2021). With multitemporal resolution offered by PlanetScope, we can assess the degree to which spectral reflectance values, which serve as proxies for a variety of environmental conditions (Jensen, 2007), change over different time scales. Within SW Madagascar, climatic and environmental variability is a constant challenge, both in terms of seasonality and longer-scale climatic variability. Based on prior research, we ask whether human landscape modifications improved resilience of environments to climatic fluctuations (*i.e.*, more stable over time with less seasonal variation [*sensu* Holling, 1973]). If so, we expect reflectance signatures and metrics of vegetative productivity at archaeological sites to exhibit less variation than surrounding areas over time.

## Methods

To assess this question, we mosaiced a collection of 98 individual PlanetScope images collected between 2018 and 2021 (orthorectified and harmonized by Planet, see Supplemental Materials). Because of the extreme seasonality in this region, we calculated the median reflectance values (following Orengo *et al.*, 2020) of recorded PlanetScope data to produce 4-year composites of the wet and dry seasons. Next, we calculated the mean seasonal change in reflectance values across four of PlanetScope's spectral bands (Red, Green, Blue, NIR, see Table 1) between seasons from 2018 to 2021 (see Supplemental Code). This period coincides with an increased incidence of drought (Ollivier *et al.*, 2023; Randriatsara *et al.*, 2022) which may affect environmental variability. Using these new multitemporal composite images, we calculate the Normalized Difference Vegetation Index (NDVI) values for the wet and dry season and seasonal change composites using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

NDVI is a commonly used vegetation index that is a proxy for biomass, vegetative productivity, and health.

Next, we extracted the mean reflectance and NDVI values of our seasonal and rate-of-change rasters for a collection of archaeological and non-archaeological



locations using a 20 m buffer (Supplemental File). This analysis was conducted using the *raster*, *sf*, *ggplot2*, and *gridExtra* packages in R v. 4.2.3 (Auguie, 2017; Hijmans, 2019; Pebesma, 2018; Pebesma & Bivand, 2023; R Core Team, 2021; Wickham, 2016). Our archaeological dataset consists of 383 archaeological sites and 61 surveyed locations without any archaeological materials investigated during fieldwork between 2017 and 2022 by the Morombe Archaeological Project (Davis, 2022; Douglass, 2016). These sites represent a mix of temporary campsites and (semi)permanent villages spanning the past several hundred to one-thousand years, demarcated by the presence of cultural artifacts like ceramics, modified shell tools, and shell beads (Buffa *et al.*, in review; Davis *et al.*, 2020, 2023).

Next, we assessed the seasonal variability in reflectance and NDVI values of archaeological and non-archaeological sites by calculating the coefficient of variation (CV). The CV compares the degree of variability within a dataset using the following formula:

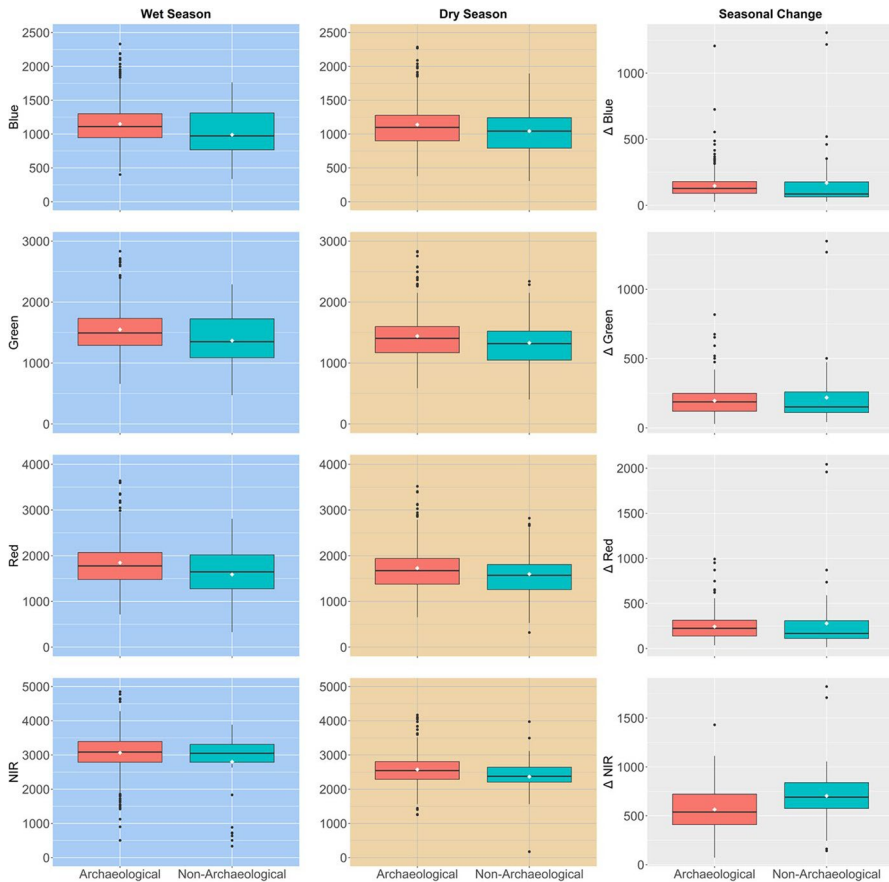
$$CV = \frac{\sigma}{\mu}$$

where  $\sigma$  = the standard deviation and  $\mu$  is the mean of the dataset. If archaeological sites exhibit more stable environmental conditions (*e.g.*, vegetation characteristics, soil properties, and moisture retention rates), we expect CV values will be lower than in non-archaeological zones.

### Insights on Resilience Among Fishing and Foraging Communities

The results of this multitemporal analysis help to illuminate the ways in which human activities have impacted the ecological stability of coastal SW Madagascar. On average, archaeological areas express slightly elevated reflectance levels and exhibit less variation over time across the electromagnetic spectrum compared with their surroundings (Fig. 4; Table 3). Within the Blue wavelength, in particular, elevated values suggest greater water availability in archaeological areas with less fluctuation between seasons over time. Higher green and NIR reflectance indicate the presence of denser vegetation and greater biomass production, and this same trend holds for NDVI values, specifically (Fig. 5). The mean NDVI values of archaeological areas are higher than non-archaeological sites in the dry season and nearly identical in the wet season. While people certainly settled in locations intentionally with specific environmental characteristics (Davis *et al.*, 2020), people also modified their surroundings to further suit their needs (Davis & Douglass, 2021).

The measured stability and density of water and vegetation at the archaeological sites suggest one of two things: (1) that people specifically chose places to settle with greater access to water and ecologically dense vegetation; and/or (2) that human activities may have led to the construction of a more stable and productive environment that aided in their survival, particularly for communities reliant on traditional subsistence economies rooted in fishing and foraging. We have evidence to support both of these conclusions. Studies have demonstrated that settlement behavior was based upon a variety of environmental resources, including access to higher quality vegetation and freshwater (see Davis *et al.*, 2020, 2022). We also know that paleoecological evidence



**Fig. 4** Reflectance values (y-axis) averaged between 2018 and 2021 for archaeological and non-archaeological sites. White diamonds represent mean values. Wilcox tests demonstrate that these differences are statistically significant in both the Wet Season ( $p < 0.001$ ) and Dry Season ( $p < 0.01$ ) for all bands, and the seasonal difference is statistically significant for the Blue ( $p < 0.002$ ) and NIR ( $p < 0.0001$ ) bands (see code in Supplemental Code file)

from the surrounding region indicates that anthropogenic landscape change accelerated between 1550 and 1750 CE (Domic *et al.*, 2021), which coincides with increasing population densities in the study region. While confirming the nature of ecosystem engineering requires an assessment of archaeological chronologies beyond the limits of the current data, we can, nevertheless, conclude that areas with histories of human activity display greater environmental stability than those without a history of human occupation. The satellite data coincides with a period of increasing drought and suggests that human landscape modifications increased ecological resilience.

By assessing trends in geophysical properties across multiple years and seasonal cycles, we are able to isolate how human activities influenced environmental characteristics in the past and present. These findings may hold lessons about future strategies for enhancing resilience and conservation efforts.

**Table 3** Coefficient of variation (CV) for archaeological and non-archaeological sites. Results calculate the variability within each season between 2018 and 2021 and the seasonal shift over the same time span

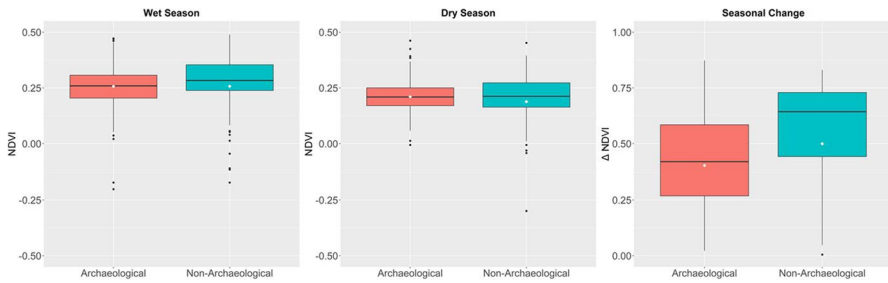
Season	Band	CV (archaeological)	CV (non-archaeological)
Wet	Blue	0.29	0.34
Wet	Green	0.26	0.29
Wet	Red	0.29	0.33
Wet	NIR	0.19	0.31
Dry	Blue	0.30	0.33
Dry	Green	0.28	0.31
Dry	Red	0.29	0.32
Dry	NIR	0.19	0.24
Seasonal difference	Blue	0.68	1.36
Seasonal difference	Green	0.54	1.05
Seasonal difference	Red	0.57	1.30
Seasonal difference	NIR	0.38	0.41
Wet	NDVI	0.332	0.556
Dry	NDVI	0.303	0.769
Seasonal difference	NDVI	0.581	0.608

## Investigating Small-Scale Field Systems in Zanzibar, Tanzania

On Unguja Island in Zanzibar, Tanzania, multitemporal satellite imagery enables a view into seasonal shifting agricultural strategies that have incrementally transformed areas of poor soil into productive agricultural landscapes, enabling communities to diversify their subsistence base as settlements shifted spatially away from the marine resources of the coast to avoid slave raiding and Portuguese naval patrols at the start of the colonial era around 1500 CE (Alders, 2022: 152–159). Archaeological field surveys and interviews with farmers in the region help contextualize the long-term, decentralized strategies that have shaped the ecosystem of this region.

Unguja is a tropical island off the coast of equatorial East Africa in the Zanzibar archipelago, settled by agricultural and fishing communities in the seventh century CE after a long period of abandonment since the end of the late Pleistocene, when sea levels rose and cut off the island from the mainland (Kourampas *et al.*, 2015; Shipton *et al.*, 2016). The island experiences seasonal temperature and rainfall patterns of the East African Swahili Coast: the winter dry season (December–February), the “long rains” (March–June), the summer dry season (July–September), and the “short rains” (October–November) (Lane & Breen, 2018).

Archaeological surveys attest that Swahili people have occupied karstic coralline limestone regions in an area of the northeast since at least the eleventh century CE (Alders, 2023), but settlement may have intensified in the colonial period as large numbers of enslaved East African mainlanders were brought to the island and as plantations dispossessed rural communities in agricultural lands to the west (Glassman, 2011; Owens, 2007). Shifting cultivation involving burning and the digging and redigging of holes in coralline limestone bedrock is necessary for agricultural

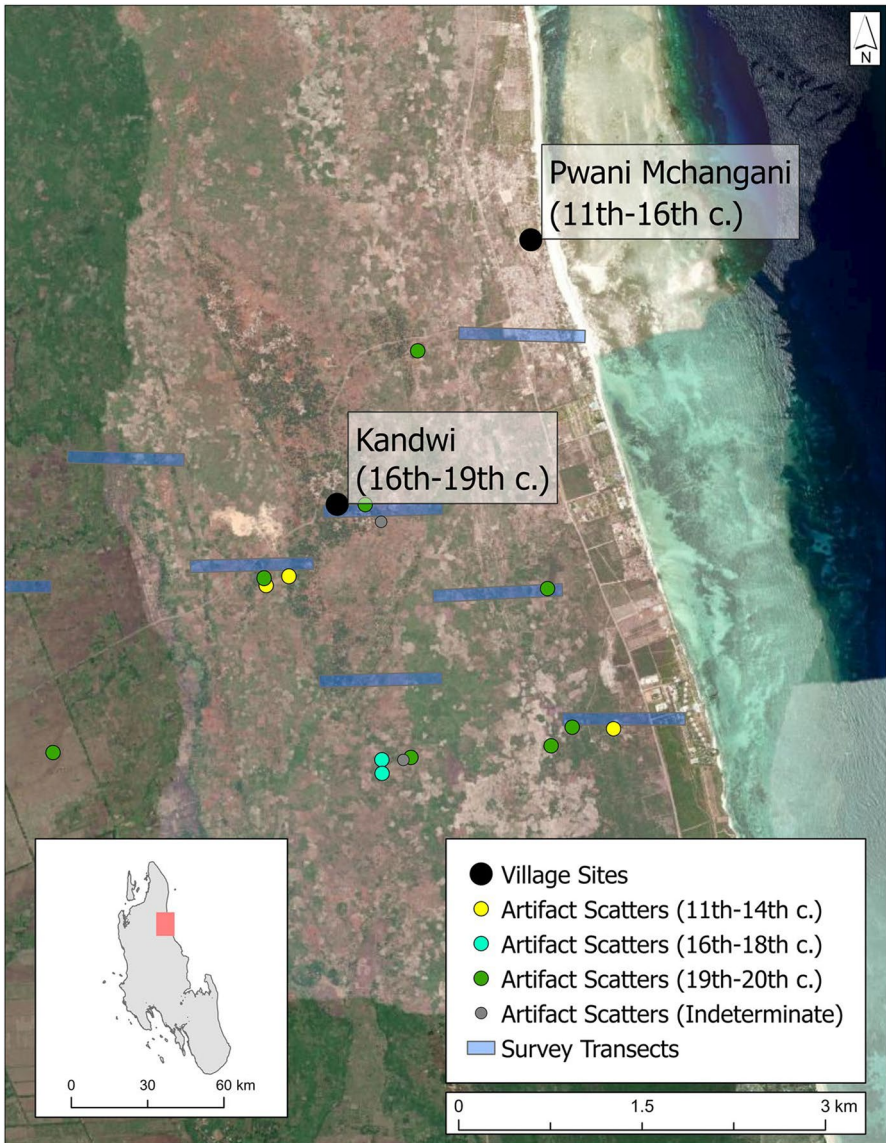


**Fig. 5** NDVI values averaged between 2018 and 2021 for archaeological and non-archaeological sites. White diamonds represent mean values

production in the rocky, shallow lateritic soils of the eastern region today, to grow root vegetables (cassava, taro, and purple yam), banana, and lentils. These practices occur around the plateau where surveys located the archaeological village site of Kandwi (fifteenth c. to present, see Alders, 2022, 2023). These practices may have also occurred along the coastal strip by the site Pwani Mchangani (eleventh–sixteenth centuries CE), but modern development has likely covered these field systems.

In addition to these archaeological village sites, surveys also recorded 14 other ceramic surface scatters dating from the eleventh to nineteenth centuries CE (see Alders, 2022, 2023 for a discussion of methods, also see Fig. 6) within open field plots around the Kandwi plateau. Based on interviews with farmers, these smaller sites are interpreted as evidence for seasonal camping and planting by farmers in the past, practicing similar agricultural techniques to those used by farmers today (Alders, 2022: 118–126). Where modern farmers use aluminum cooking pots, earlier Swahili people would have used ceramic carinated cooking vessels. And while people today bring plastic water jugs to these areas (see Fig. 7), earlier inhabitants may have brought Indian red earthenware *mitungi*, or water jugs. Some finer eating ceramics were found in field plots as well: these included blue and white porcelain bowls imported from Asia, an open bowl base of glazed Bahla ware from Oman, European glazed whiteware, and a few small pieces of eleventh–fourteenth century late Sgraffiato ware from the Persian/Arabian Gulf (see Horton, 1996 for comparisons).

We hypothesized that incremental landscape modifications like burning, field wall construction, and the digging and re-digging of holes in the coralline limestone bedrock occurred historically along an inland corridor between the two village communities of Kandwi and Pwani Mchangani, from at least the sixteenth century CE. One way to test this is to determine whether modern seasonal land use is concentrated between these two archaeological sites; this might suggest that long-term anthropogenic changes have made field systems in these areas more productive and therefore more desirable to modern farmers. Mapping modern field systems in this area is difficult from the ground, since the rocky landscape and overgrown brush limits field surveys. Furthermore, field systems are not static, so high-spatial-resolution investigations of the field system (*e.g.*, with imagery from Google Earth



**Fig. 6** Sites and surface scatters in northeastern Unguja, in Zanzibar, Tanzania

or the free, open-access drone imagery from the Zanzibar Mapping Initiative) fail to capture seasonal and multi-year spatial diversity of field plots. Any individual image will only reflect field plots that were open on a single day. To address this, multitemporal and multispectral PlanetScope data from four different seasons were reclassified and segmented into image objects in eCognition (v. 10.3, Trimble Germany GmbH 2022). This enabled a seasonal approach to understanding the spatial



**Fig. 7** Photo of a recently cleared field in the limestone bedrock areas around the Kandwi plateau, planted with banana trees. A plastic water jug left by modern farmers reflects long-term trends of camping in fields for planting

extent, form, and emergent characteristics of shifting agricultural strategies in this region. Delineating the extent of field systems in this region may inform a spatial understanding of how Swahili people developed resilient agricultural systems to persist through colonial transformations.

## Methods

To delineate and map the spatial extents of the swidden field system, the following methods were used:

1. First, we selected four cloud-free, 4-band PlanetScope images (orthorectified and harmonized, see Supplemental Materials) of a 35 km<sup>2</sup> study area around the Kandwi plateau, in an area visually assessed to contain swidden field plots in coralline limestone bedrock areas (see Hardy *et al.*, 2015)—one for each season (Dry-Hot, Long Rains, Dry-Cold, and Short Rains). These images are listed in Supplemental Materials, and show the island during the months of January, April, July, and November. They were captured between 2018 and 2021. Seasons are not contiguous due to a lack of cloud-free imagery available across contiguous seasons. They capture the temporal span of four different rainfall seasons in Zanzibar. Mean rainfall during these seasons varies from approximately 50 mm of rain during the two dry seasons, to 200–350 mm of rain during wet seasons (Camberlin *et al.*, 2009; Nicholson, 2017). The footprint of the imagery used is denoted by the polygon shown in Fig. 8.

2. Second, we visually inspected PlanetScope imagery in True Color and used a masking tool in ArcGIS Pro to remove features unrelated to agricultural field systems in karstic limestone areas, like the Kandwi plateau itself (planted with fruit orchards), several permanent rice fields in deeper soil areas of the far west, and a strip of modern hotels and houses in the far east. Comparisons with soil, geology, and land use maps (Hardy *et al.*, 2015; Khamis *et al.*, 2017) aided our determination of non-relevant areas. These areas were removed to ease subsequent processing in eCognition (see below).
3. Third, we imported these images into eCognition (v. 10.3 Trimble Germany GmbH 2022) to carry out an object-based image analysis (OBIA) of the landscape (see Blaschke, 2010; Blaschke *et al.*, 2014; Davis, 2019). We conducted a multiresolution segmentation of each image weighted by the near infrared (NIR) band. Multiresolution segmentation is a method of grouping pixels into similar segments with shared characteristics (or image objects) that uses an iterative process to group objects based on a variance threshold across the attributes of shape and compactness (see Watkins & Van Niekerk, 2019). For this analysis, we used a scale parameter of 40, a shape factor of 0.1, and a compactness factor of 0.5. These were default parameters that we adopted because they produced image objects that align well with previously recorded fields in this region. Different settings in multiresolution segmentation might produce different results, but we chose to forego additional experimentation with parameters out of consideration for time and processing power.
4. Fourth, we created four NDVIs, one for each seasonal raster, using the NDVI process in eCognition, following the same formula and image bands as specified in the Madagascar case study.
5. Fifth, we classified image objects for each season using two different sets of NDVI thresholds (one for November/January and one for April/July) (Table 4) determined through visual comparisons with high spatial resolution (~7 cm) drone imagery from the Zanzibar Mapping Initiative (<http://zansea-geonode.org>, though this website appears to be no longer functional). Image objects for each season were classified as scrub vegetation (areas possibly left fallow for many years or even decades, but indistinguishable from natural scrub within the scope of this study), old or cultivated fields (fields with low levels of vegetation, cleared in the past year or two), newly open fields (recently burned, bare earth fields), developed areas (houses), and other areas of exposed coralline limestone bedrock.
6. Next, we created a raster composite from all four images using the Raster Calculator in ArcGIS Pro showing the total extent of cultivated areas across four seasons, from 2018 to 2021.

**Table 4** The knowledge-based classification NDVI thresholds for different seasons

Classes	Nov/Jan NDVI thresholds	Apr/Jul NDVI thresholds
Scrub/vegetation	0.44 and above	0.59 and above
Old/cultivated fields	0.32 to 0.44	0.41 to 0.59
Newly exposed fields	0.14 to 0.32	0.29 to 0.41

**Table 5** Classified field image object comparisons and composite of open fields

	Newly opened fields (ha)	All open fields (ha)
January 2021	9	323
April 2019	39	298
July 2018	5	164
November 2018	43	332
Composite of open fields		762

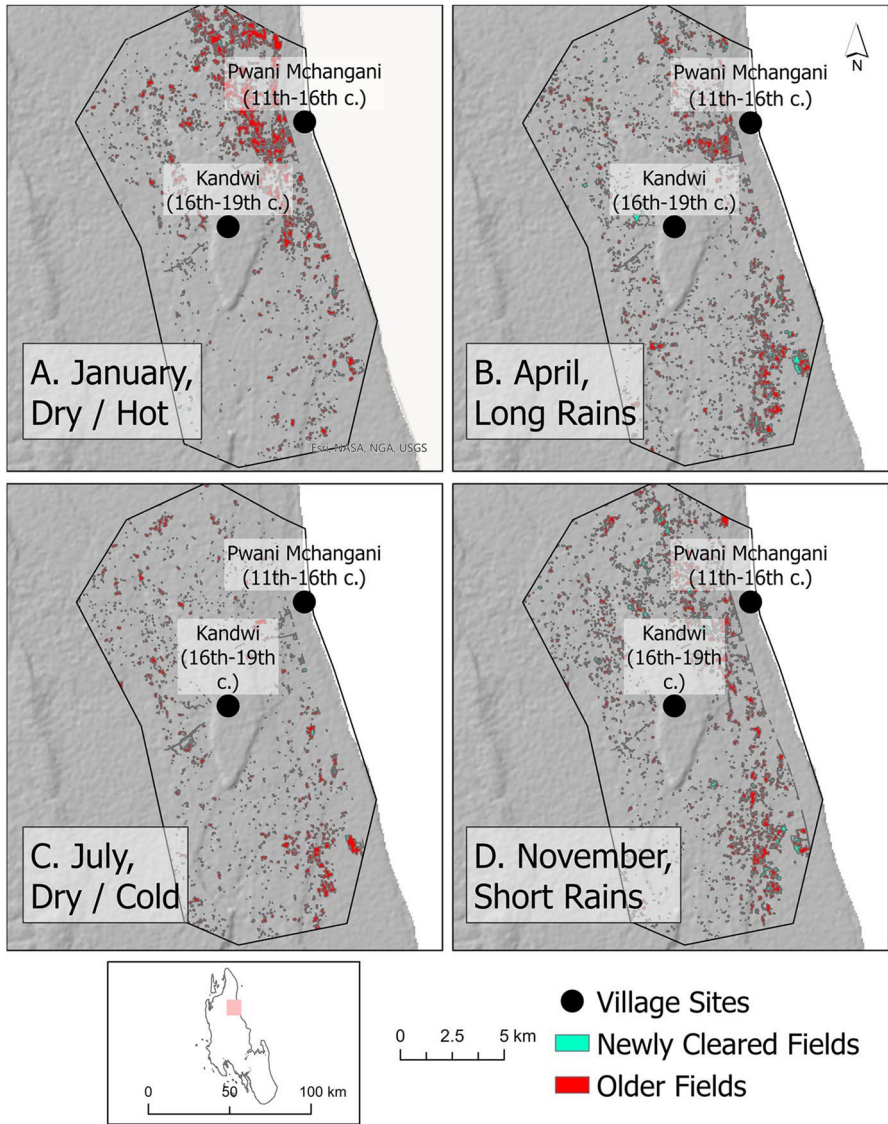
7. To achieve a quantitative measure of field density, a 1-km buffer zone was created from the modern road that connects the sites as well as from a least-cost path from Kandwi to Pwani Mchangani (based on free Shuttle Radar Topography Mission (30 m) elevation data), approximating historical pathways between the sites. In this buffer zone, we calculated a preliminary measure of field density.

## Results

Table 5 shows a summary comparing the results for newly opened vs. all open fields in hectares, for each season. The results confirm farmer interviews describing planting as primarily occurring during March and October; accordingly, more newly opened fields are visible in the following months of April and November, respectively. Accuracy assessments of these classifications were carried out in eCognition using the Accuracy Assessment Tool and a sample of over a hundred field sites for each image that WA manually identified from visual inspection of the same imagery in false-color and true-color. Overall accuracy values are 80% or higher for all seasons (see Supplemental Materials for the full statistics, including producer's and user's accuracy for each season). Accuracy assessments are preliminary, as additional ground verification of field boundaries is needed. Despite this limitation, our evaluation demonstrates that the classification results reveal real aspects of the shifting cultivation system on the island, and this data may set groundwork as a preliminary step in future research. Figure 8 shows examples of classified fields from four seasons.

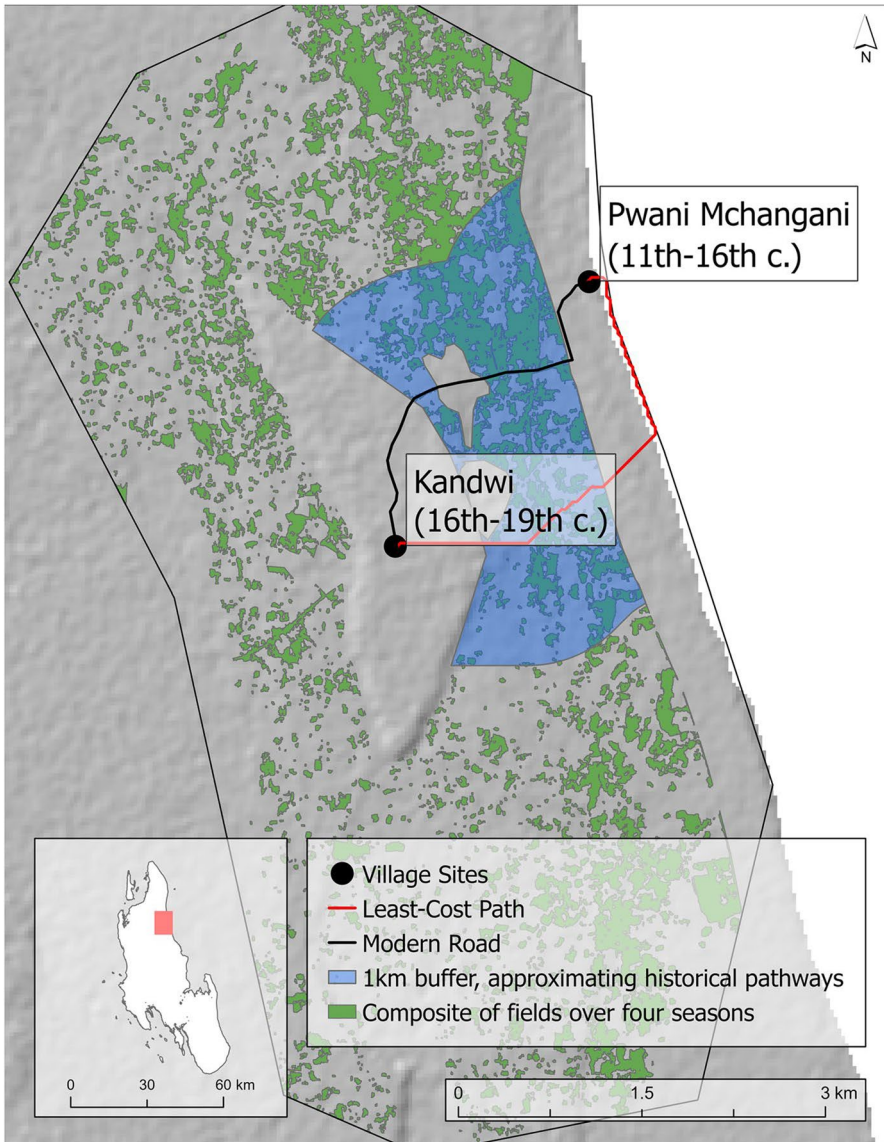
While these seasons are not all within the same year, a non-summative composite of their areas nevertheless more closely reflects the total cultivated area of the swidden field system around Kandwi, compared to a snapshot from any single date. Figure 9 shows the composite. Green polygon areas reflect combined newly opened and recently fallow fields across the area of interest. Gray areas beyond reflect non-agricultural areas, as well as scrub, forest, or other forms of non-shifting land use. Some scrub areas may be places that have been left fallow for many years, a practice common in many forms of African swidden agriculture (see Höhn & Neumann, 2012; Netting, 1993). However, distinguishing very old fallow fields from pristine scrub and woodland in the eastern region of the island is beyond the scope of this project. From NDVI analysis, we have only been able to differentiate cleared fields (mostly devoid of vegetation) and recently opened fields, which appear similar to bare earth soils and ash as a result of recent burning and cutting.





**Fig. 8** Field objects during four rainfall seasons: **A** January (Dry/Hot), **B** April (Long Rains), **C** July (Dry/Cold), and **D** November (Short Rains). The polygon represents the general extent of the field system (determined through visual inspection in true color) and the footprint of the images used (see Supplemental Materials)

A qualitative assessment of the density of field objects shows that fields are most common in the corridor between the Kandwi plateau and the sea and may also cluster specifically between the sites of Kandwi and Pwani Mchangani. As detailed in the methodology, a density measure within a buffer zone (~439 ha) created from the



**Fig. 9** Composite of all fields (old and new) from four seasons, a least-cost path and the digitized modern road between the sites, and a hypothetical 1-km buffer zone from these roads approximating historical pathways between Kandwi and Pwani Mchangani

modern road and the least-cost path between sites gives a preliminary quantitative measure of land use intensity between the historical village sites. In this buffer zone, field objects cover 176 ha, approximately 40% of the total space. Outside the buffer zone (~2503 ha, the total region excluding the buffer zone and removed areas, like the plateau and urban space on the coast), field objects cover 587 ha, approximately

23% of the total space. Overall, the results suggest that swidden agricultural patterns cluster between the Kandwi Plateau and the coast and are specifically dense along possible historical pathways between the archaeological sites of Kandwi and Pwani Mchangani. This pattern may attest to the impact of historical settlement trends in shaping the seasonal patterns of modern land use. As cultivators traveled and shifted between these two sites, they cleared brush and enriched soils through burning and digging in ways that have impacted the modern seasonal use of the areas around the Kandwi plateau. As this case study demonstrates, seasonal PlanetScope data can help reveal temporal patterns in land use that are absent when viewing archaeological landscapes from a static perspective. Accounting for seasonal variations in modern field systems is necessary to analyze interconnections between long-term agricultural patterns of shifting cultivation and ancient settlements, contributing to an understanding of linkages between historical and contemporary African farming systems (Davies *et al.*, 2016). Finally, these results also clarify the areas where future archaeological surveys might be planned to further recover material culture related to mobile shifting cultivators on the island. The largest field clusters detected in this analysis lie to the northeast and southeast of Kandwi and may indicate the presence of other significant areas for future research. It is expected that a future systematic survey would reveal the greatest concentrations of archaeological remains in these densely farmed areas.

## Delineating Monocropped Sugar Cane Field Systems in Mauritius

Mapping field systems is a concern for anthropologists globally since the spatial dimensions of fields and their relation to other environmental, archaeological, and contemporary sociocultural features inform an understanding of agricultural production in the past and present. Our last case study examines the uses of multitemporal imagery in landscapes of large-scale intensive monocropped agriculture on the island of Mauritius.

Archaeological research on Mauritius has brought forward the complex relationships that emerged between settler colonists, enslaved and indentured people, and their free descendants over the last 500 years on this previously uninhabited island. Enslaved and indentured people transformed the island into a settler trading port/waystation and later a sugar cane colony during the seventeenth to nineteenth centuries under Dutch (1638–1710), French (1715–1810), and British (1810–1968) colonial governance. Excavations of plantations, cemeteries, forts, ports, and quarantine stations have contributed to our understanding of the experiences of Asian and African laborers and the broader context of colonial experimentation with settlement, governance, land use, emergent agro-capitalism, and labor exploitation (Čaval, 2023; Čaval & Cianciosi, 2023; Floore & Jayasena, 2010; Haines, 2019, 2020; Haines & Hauser, 2023; Seetah, 2015; Summers, 2021; Mungur-Medhi, 2019). As it is one of the few plantation colonies that had no indigenous population, Mauritian archaeology provides a unique opportunity to examine the ecological impacts of colonialism on native environments (Haines, 2021; Seetah *et al.*, 2022).

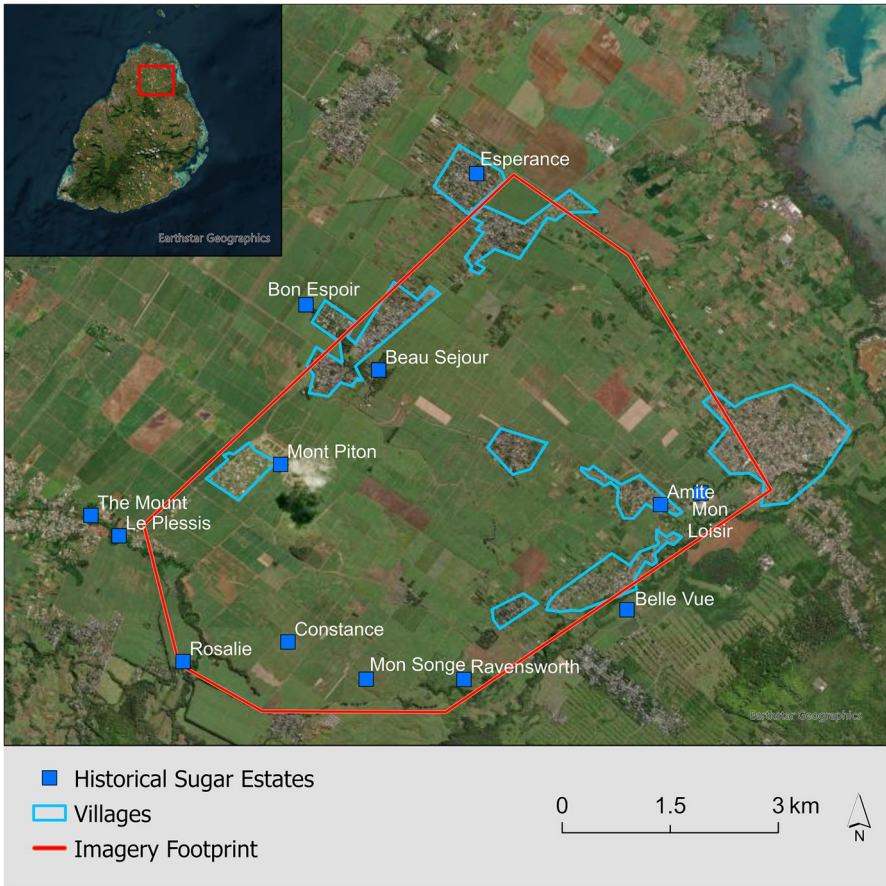
Here, we use PlanetScope data to answer a key archaeological question: To what extent do modern agricultural landscapes in Mauritius reflect colonial plantation legacies? Archaeological studies of plantation landscapes usually focus on the configurations of domestic, industrial, and agricultural zones within one estate. Agricultural field boundaries reflect colonial spatial practices; therefore, increasing our scope to focus on a plantation *region* positions the landscape of monocropping within the larger socioecological system.

Sugar cane agricultural fields define much of the Mauritian landscape today. In their latest report, the government's Statistics Mauritius (2022) reported that sugar cane was harvested from 39,199 ha (21% of the island). Nigel *et al.*'s (2015) study of landcover analyzed a single 1994 SPOT XS satellite image of the entire island with blue, green, and infrared bands; using OBIA, they quantified different forms of land cover and found that approximately 54.1% of the 1859 km<sup>2</sup> island was sugar cane fields. Their data was limited by the expense of acquiring more than a single image with about 10% cloud coverage. It is unclear why the results of these two reports are so dramatically different, but both highlight the continued importance of the crop to Mauritius. Cane growing and production technologies have changed drastically over the last 200 years, and the majority of historic mills and other estate infrastructure buildings were abandoned in the last century as cane processing was centralized to three main mills; however, we suspected that sugar cane fields that are in use today have been in continuous use since the colonial period. Other methods for delineating field systems may include on-the-ground field surveys, but these are time-consuming and expensive for a large-scale project, and manual digitization of satellite imagery through tracing takes considerable time and is reliant on the interpretative perspective of a tracer. In comparison, newly available data from PlanetScope may significantly increase the capacities of researchers to accurately quantify field systems on Mauritius.

In this case study, we expected that the analysis of multitemporal data would provide a comprehensive way to document field systems across large areas and could, subsequently, improve estimates of historic plantation boundaries by identifying cultural features within fields that are less visible during certain times of the year. Secondarily, we expected that the delineation of contemporary sugar cane fields, assessed against historic maps, would illustrate the spatial relationship between historic plantation mills and laborer domestic quarters, their subsequent transition to villages, and more recent urban development.

### Creating Image Objects of Sugar Cane Fields

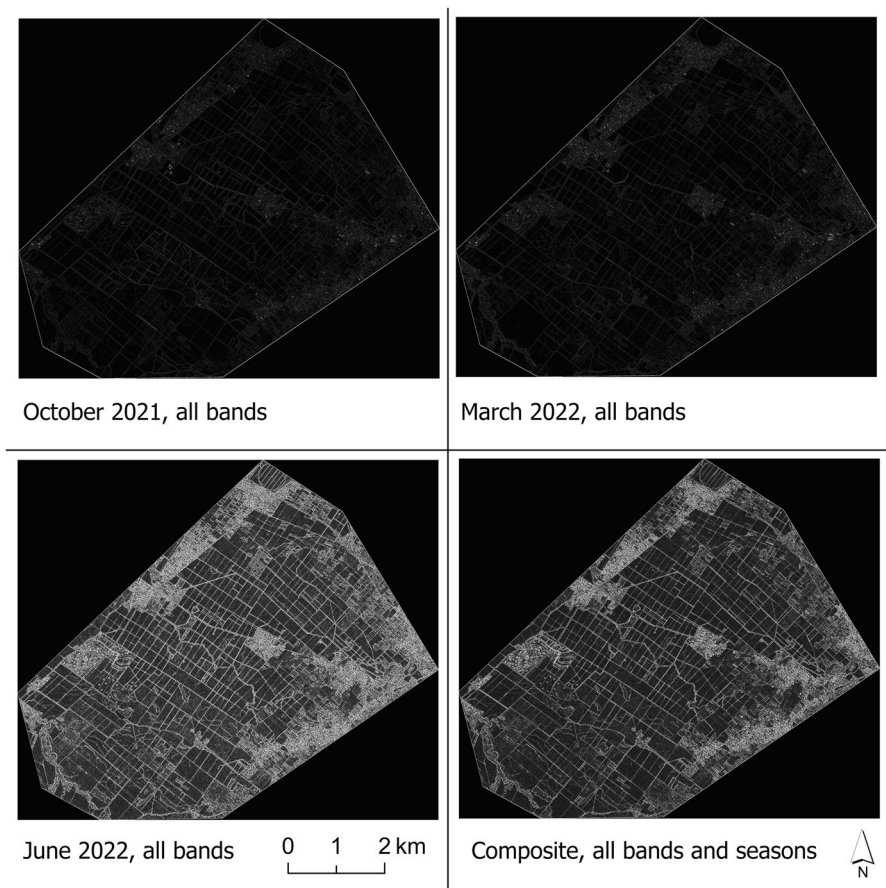
The northern region of Mauritius is of lower elevation and relatively flatter than the more mountainous southern half. As such, it continues to be a prime area for sugar cane production. To test the applicability of PlanetScope data for mapping field systems in this region, we established a remote sensing methodology that distinguished and quantified field systems in a 35 km<sup>2</sup> area in the central northern region of Mauritius which includes five former nineteenth-century sugar cane mills that were part of the estates of Mont Piton, Gokoola, L'Amitié, and Antoinette, several smaller land holdings, and villages that developed between sugar cane estates (Fig. 10).



**Fig. 10** Area of study in Mauritius. Esri World Imagery with 0.6–1.2-m resolution are used as base maps to show landscape features such as urban space, field stones, roads, and architectural buildings as distinct from delineated fields (Esri, Maxar, Earthstar Geographics, and the GIS User Community). The locations of historical sugar estates are from a historic map (Descubes, 1880)

Using the same initial OBIA steps previously described in step 3 for the imagery from Zanzibar, we drew on the approach of Watkins & Van Niekerk (2019) and adapted it to the specific conditions of this field site. Seven 4-band PlanetScope images (orthorectified and harmonized) from four different seasons throughout the year—March 2021, October 2021, January 2022, and June 2022—were chosen for their complete coverage of the area selected and lack of cloud interference of the 35 km<sup>2</sup> area (see Supplemental Materials). The images were processed through an edge extraction algorithm for each band (Red, Green, Blue, and NIR) of each image in eCognition using the Canny algorithm (lower and higher thresholds of 0, Gauss convolution Full Width at Half Maximum (FWHM) of 1), producing 16 total edge extracted rasters, following Watkins & Van Niekerk (2019). We summed these using a raster calculator in ArcGIS Pro, producing a composite that accentuated

permanent features and edges while removing noise caused by seasonal vegetation changes. All sixteen edge rasters can be found in Supplemental Materials, but Fig. 11 compares the composite raster to three examples of band composites from single seasons. White lines indicate the edges of agricultural fields with distinct boundaries defined by roads, rock piles, urban structures, and tree groves. Visual inspection shows significant variation between seasons in terms of edge results—October 2021 and March 2022 produced faint outlines of fields, while June 2022 produced good field boundary edges, but also a significant amount of noise within fields. Our visual assessment is that a composite edge layer derived from all seasons of imagery provides the best result, producing clean edge boundary lines while minimizing noise within fields. Creating a composite of multiple seasons reduces noise caused by differences in plant growth on any individual day and enables an accurate delineation of field boundaries. Permanent non-vegetative features within



**Fig. 11** Field boundary edges from composites of seasons, compared to the composite raster of edges extracted from all seasons and bands. All 16 season/band edge rasters used to make the composite can be found in Supplemental Materials

fields were highlighted and enhanced, thus increasing the likelihood of capturing low ground features that might be hidden under foliage during different seasons.

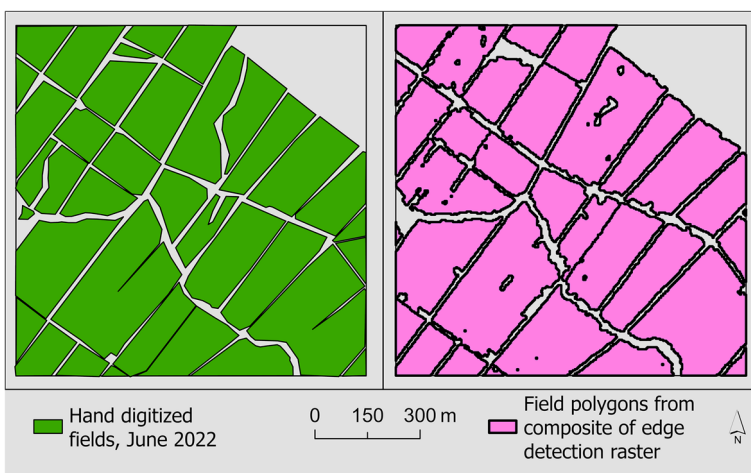
On the multitemporal seasonal composite, we used a watershed segmentation function in eCognition to create image objects that correspond to field boundaries (Neighborhood 8—connected, seed criterion: Overflow Height, threshold 0.2). Then, we performed a knowledge-based classification of image objects in eCognition, using “brightness” (0.1) to classify edges and “area conditions” (> 800 pixels) to distinguish fields. Further, noise removal is an optional step in agricultural applications of this method, but we chose to include this non-vegetation related noise for archaeological applications since it likely reflects the presence of permanent features within field systems, like basalt stone piles.

To assess this model for accuracy, we extracted the field class as a polygon file and compared it visually to hand-digitized fields from a 1 sq. km sample of the June 2022 image, which was visually determined to show the most distinct field boundaries in true and false color images. Figure 12 shows a comparison between hand digitization and the extracted field polygons derived from the edge detection algorithm.

Visually, the accuracy of this classification method is apparent both qualitatively (from visual comparison) and quantitatively (see Supplemental Materials). Overall accuracy was 92%. As such, the classification method proves to be a fast and accurate way to digitize large field regions.

### Between Fields and Features

To investigate relationships between field systems and historical settlement, extracted field polygons were brought into ArcGIS Pro and compared with underlying ESRI basemaps and a georeferenced historical map (Descubes, 1880). Comparing our OBIA results with the resulting field polygons positioned over a georeferenced historic map created in 1880 (Descubes) demonstrates how Mauritius’

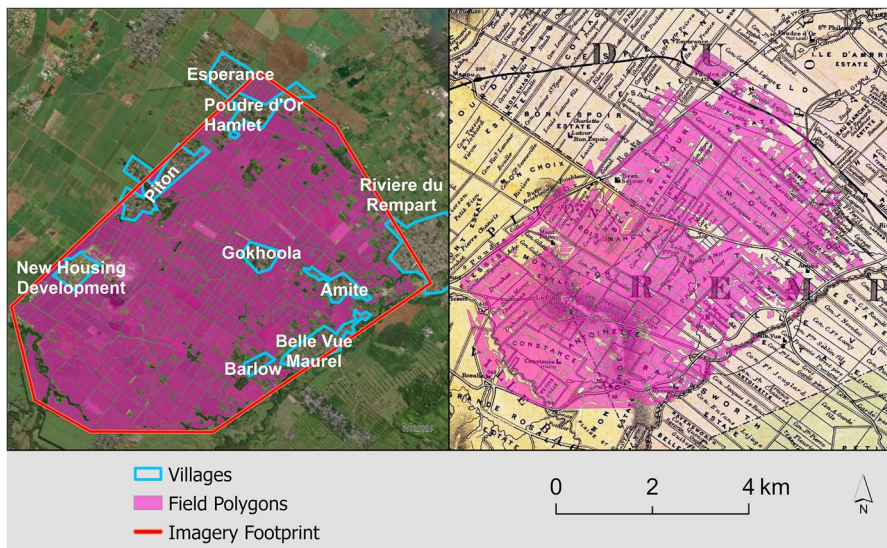


**Fig. 12** Comparison between hand digitized and automated agricultural field polygons

landscape was transformed simultaneously by cultural and ecological forces, as colonial planters prioritized sugar cane monocropping while descendants of enslaved and indentured laborers established towns and villages at the borders of such plantations (Fig. 13). The historic map, itself a palimpsest, not only reflects contemporaneous land holdings, but also includes references to the names of former owners of estates on some properties and replicates historic property boundaries, central sugar cane mills that were in use during the eighteenth and nineteenth century, and roads. Road features and demarcated property boundaries on the 1880 map are geometrically aligned with our OBIA generated field objects, demonstrating that the spatial configurations of fields remained consistent from the colonial period.

The villages of Piton and Gookoola stand out as situated between sugar cane fields and adjacent to sugar cane estates, suggesting that further research is needed to understand the iterative spatial relationship between estates, villages, and agricultural fields. It is still unclear why the core industrial and domestic zones of some sugar estates developed into villages and others were abandoned as sugar cane milling was centralized and smaller estate mills closed. Comparing changes in land use over time around both contemporary villages and along the western edge of the survey area illustrates how urban development has expanded within the modern landscape. For example, the rectangular property plots on the 1880 map in the southeastern corner of Gookoola suggests that the land may have been cultivated at one time but was subdivided into house plots within the last 100 years (Fig. 13).

The resulting object visualization also brings forward features of note that exist within the fields but would only be visible when the fields are cleared. In several fields in our test area, they have made large basalt stone piles to clear the fields rather than displacing the rocks into field rows, highlighting a specific agricultural strategy (Fig. 14). Mauritians



**Fig. 13** Left, comparison of field polygons with known historical villages; right, comparison of field polygons with Descubes (1880) *Map of the Island of Mauritius*





**Fig. 14** Sugar cane field with basalt boulder piles (left) excluded from field polygons (center). Hindu shrine in sugar cane field distinguished from surrounding vegetation (right)

cope with field stones in different ways around the island, including displacing them into rocky lines, pyramids, and walls and boring holes in the bedrock. This process visibly delineates monocropped land from other land uses, altering the underlying fabric of the island in the process. We can also see features that might be worth examining either with higher resolution imagery or through a ground survey. Around the island, the ruins of abandoned sugar cane estates are often obscured within agricultural fields that have been in continuous use since the early nineteenth century, identifiable only by mill chimney stacks that protrude above the sugar cane at full height or when the sugar cane is cut. The edge extraction process also distinguished a Hindu shrine and the pathway to access it from the surrounding field system (Fig. 14). These features are visible from satellite imagery when the sugar cane is cut in either June/July or October/November; however, the edge extraction process works best when fields are green and brighter, emphasizing again the benefits of using multitemporal imagery particularly for large regions. Our analyses suggest that landscape practice in Mauritius is simultaneously iterative and cumulative; the configurations of field plots, village settlements, and plantation estates have accumulated within the landscape while also continuing to inform present land uses.

This methodology for conducting systematic regional surveys of archaeological sites, enabling the straightforward quantification of field areas for individual plots, has applications for archaeologists working in agrarian landscapes. These methods may aid archaeologists in mapping historical field systems and quantifying their spatial relationships with known settlements.

## Discussion

The methods outlined in our case studies above offer ways to approach the problem of quantifying landscape systems while taking temporal change into account. Especially in parts of the Global South where LiDAR data is not easily available and where cloud cover and heavy tropical vegetation may obscure field boundaries visually, integrating multitemporal perspectives afforded by PlanetScope satellite

imagery is crucial for considering emergent landscapes shaped by seasonal anthropogenic activities.

The methodological approaches outlined here go beyond the identification and recording of archaeological features in a static landscape, and instead model the long-term persistence of anthropogenic landscape change. The metaphor of the landscape as a palimpsest—consisting of residual layers that are created, changed, and accumulated over time—has been useful for archaeologists grappling with the temporality of a place while using traditional datasets that portray landscapes as static snapshots (Bailey, 1981; Binford, 1981; Crawford, 1953; Randall, 1934). Given the predominant methods of cartographic representation in archaeology that consist of layers of features within a given space, temporal dimensions are reduced into agglomerations that constitute the archaeological present (*sensu* Bailey, 2007). This view of temporality de-emphasizes the emergent nature of landscape systems, instead portraying archaeological landscapes as static. But multitemporal analysis of landscapes can reveal the trajectories and seasonality of landscape change itself, and these technologies may entail a rethinking of how archaeologists should represent landscape temporality more broadly (*e.g.*, Carleton *et al.*, 2023; McGrath *et al.*, 2022; Menze & Ur, 2012; also see Sinclair *et al.*, 2018). Namely, large datasets of multitemporal satellite imagery like those produced by PlanetScope can allow archaeologists to see landscape change at different temporal scales. Considerations of seasonality in modern landscapes can reveal patterns that may shed light on past archaeological land use, as the case studies here have shown.

For example, our case study on Madagascar demonstrates how the analysis of multitemporal satellite data shows that ecological signatures at small-scale fishing and gathering sites are more stable in terms of water and vegetation seasonally compared to non-archaeological areas, suggesting that humans may have chosen more stable locations for permanent occupation and/or modified their local environments in ways that enabled long-term sustainability (see also Davis & Douglass, 2021). In Zanzibar, multitemporal data enables reconstruction of seasonal change in swidden field systems, revealing the spatiotemporal trends of land use in relation to archaeological village sites. In Mauritius, multitemporal data allows for a more accurate reconstruction of a historical plantation field system that de-emphasizes seasonal variation in vegetation and reveals permanent contours of landscape modification.

Whether viewing landscape change by investigating seasonal small-scale modifications or by time-series approach using historical imagery (*e.g.*, Menze & Ur, 2012; Casana, 2020), multitemporal datasets enable a conceptualization of landscape formation in a way that does not rely on a fixed archaeological present, but the unfolding of seasonal, annual, or decadal changes to landscapes and cultural sites. We do not aim to reject the concept of the palimpsest but to fully theorize and operationalize the approaches implied by the palimpsest perspective. This requires a multidimensional viewpoint that captures emergent landscape systems, rather than reducing these dynamics into static endpoints. Multitemporal approaches are one way to enable a compositional or seasonal view of landscapes as complex, emergent systems that follow non-linear patterns of evolution where past and present are often intertwined and interdependent (see Sinclair *et al.*, 2018).

These methods allow us to engage with broader anthropological literature focused on understanding the ways in which the past both informs the present and how our present conditions influence the ways we engage with the past (McKittick, 2013; Thomas, 2016). Rather than relying only on one linear notion of time, multitemporal imagery allows for the cyclical nature of the changing of the seasons and the ebb and flow of climatic shifts. A tenet of archaeology is that the past exists in the present, an important framing for understanding the socioecological systems as both *in* the present and *of* the past in the present (see also Magnini & Bettineschi, 2019). While our methodologies often result in the production of a series of static images, they are representations of the simultaneity of past, present, and future.

## Conclusion

Multitemporal remote sensing data is invaluable for studying emergent socioecological systems and piecing together insights about the impacts of human activities on landscapes. Multitemporal data from satellite sensors spans back over 50 years with programs like Landsat. Over the past half century, improvements in spatial, temporal, and spectral resolution have led to new satellites like Sentinel-2, and most recently, PlanetScope. Despite PlanetScope's shallower time depth compared to long standing satellite programs like Landsat, its high spatial resolution (3-m) and high revisit time permit for a range of analyses on small-scale activities and incremental landscape transformations at the level of the individual site or field. Longstanding missions like Landsat will remain important for large-scale considerations of environmental change over regions over the past half-century, but the emerging availability of data from Planet Inc. will change the types of questions that archaeologists can address. Small-scale investigations of local and micro-environmental impacts that long proved beyond the capacities of Landsat and even Sentinel will become possible due to Planet's availability and 3-m spatial coverage.

Multitemporal satellite imagery from PlanetScope has enabled the reconstruction of ephemeral small-scale activities and larger incrementally produced agricultural systems in tropical environments, such as Madagascar, Zanzibar, and Mauritius. Delineating patterns of land use is a concern for archaeologists since the spatial dimensions of human subsistence activities and their relation to archaeological sites inform understandings of adaptation, resilience, and the organization of production in the past. The case studies described here also have wide applicability for modeling field systems and investigating anthropogenic and archaeological landscape signatures globally, in regions where vegetation cover makes visual or automated inspection of archaeological features more difficult. The near-daily global coverage offered by PlanetScope and its ability to be accessed with a free academic license means that archaeologists have more opportunities than ever before to investigate seasonal trends in landscape change. It is hoped that as PlanetScope datasets grow, more data will become freely and openly available, further expanding the utility of this resource. While GIS-based maps of

archaeological features portray landscapes as accumulated nodes of human activity, new remote sensing datasets like multitemporal PlanetScope data permit archaeologists to represent the trajectories and seasonal cycles of landscape change more readily.

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**Data Availability** Data used in this research is available in the Supplemental Materials and Supplemental Code.

## Declarations

**Competing Interests** The authors declare no competing interests.

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