Remote Sensing Reveals Lasting Legacies of Land-Use by Small-Scale Foraging Communities in the southwestern Indian Ocean

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Abstract

Archaeologists interested in the evolution of anthropogenic landscapes have productively adopted Niche Construction Theory (NCT), in order to assess long-term legacies of human-environment interactions. Applications of NCT have especially been used to elucidate co-evolutionary dynamics in agricultural and pastoral systems. Meanwhile, foraging and/or highly mobile small-scale communities, often thought of as less intensive in terms of land-use than agropastoral economies, have received less theoretical and analytical attention from a landscape perspective. Here we address this lacuna by contributing a novel remote sensing approach for investigating legacies of human-environment interaction on landscapes that have a long history of co-evolution with highly mobile foraging communities. Our study is centered on coastal southwest Madagascar, a region inhabited by foraging and fishing communities for close to two millennia. Despite significant environmental changes in southwest Madagascar's environment following human settlement, including a wave of faunal extinctions, little is known about the scale, pace and nature of anthropogenic landscape modification. Archaeological deposits in this area generally bear ephemeral traces of past human activity and do not exhibit readily visible signatures of intensive land-use and landscape modification (e.g., agricultural modifications, monumental architecture, etc.). In this paper we use high-resolution satellite imagery and vegetative indices to reveal a legacy of human-landscape co-evolution by comparing the characteristics—vegetative productivity and geochemical properties—of archaeological sites to those of locations with no documented archaeological materials. Then, we use a random forest algorithm and spatial statistics to quantify the extent of archaeological activity and use this analysis to contextualize modern-day human-environment dynamics. Our results demonstrate that coastal foraging communities in southwest Madagascar over the past thousand years have extensively altered the landscape. Our study thus expands the temporal and spatial scales at which we can evaluate human-environment dynamics on Madagascar, providing new opportunities to study early periods of the island's human history when mobile foraging communities were the dominant drivers of landscape change.

1 Introduction

Among archaeologists, the identification and quantification of feedbacks between past human activities and landscape-scale transformations have historically focused on economies of scale that generate highly visible changes to landscapes (e.g., monumental architecture, intensive agriculture, shifts from forests to grasslands, etc.). In contrast, activities associated with small-scale mobile foraging economies have generally been portrayed as "low impact" (Stephens et al. 2019; Smith 2001). In regions around the world, like the Amazon, this line of thought has been compounded by legacies of settler colonialism and the processes of industrialization of land and resource use, resulting in narratives that downplay, obscure, or erase earlier (and subtler) traces of human landscape use (Douglass and Cooper 2020; Heckenberger and Neves 2009). Uses of remote sensing technology (i.e., satellite images) in such contexts have successfully identified these "low-impact" signatures of human action on large geographic scales (Lombardo and Prümers 2010). While predictive models have been used around the world to narrow the search for ephemeral archaeological deposits (Davis et al. 2020; Kirk, Thompson, and Lippitt 2016; McMichael et al. 2014), the use of automated remote sensing in archaeology remains skewed toward landscape modifications that are easy to identify because of their lasting marks and effects (Davis 2021; Tarolli et al. 2019).

Prior remote sensing analyses on Madagascar have focused on the drivers of settlement and mobility (e.g., resource availability and social aggregation) using predictive models based on satellite-derived environmental information and statistical modeling (Davis et al. 2020; Davis, DiNapoli, and Douglass 2020). To fully understand settlement patterns, however, we must also look at the ecological effects of human occupation (Figure 1). Therefore, in this paper, we focus on identifying and characterizing legacies of forager activities and coastal settlement on the landscape of the Velondriake Marine Protected Area of southwest Madagascar, a region with a history of coastal foraging that extends back at least to 2000 cal year BP (Figure 2; Douglass et al. 2019). The climate of southwest of Madagascar is defined by a wet season and a dry season. The region is extremely arid, receiving less than 50cm of rainfall annually, and is home to highly endemic flora and fauna which varies according to the underlying geology (Douglass and Zinke 2015). The Velondriake region sits on a Quaternary dune system composed of sandy-shell and limestone coastal rock outcrops, while further inland the geology is characterized by Pleistocene and Eocene geological systems (Besairie 1964). Vegetation in Velondriake is largely xerophytic and classified as a "spiny thicket" ecoregion, which contains some of the highest levels of endemic flora on the island (Gautier and Goodman 2003). The people living in coastal Velondriake today primarily identify as *Vezo* (roughly translated as "to paddle") and center their livelihood on the sea (Astuti 1995). The area has been inhabited for thousands of years by communities practicing foraging and fishing, as well as agropastoralism over the past several hundred years (Douglass et al. 2018; Hixon et al. 2021).

[Figure 1]

In this article, we investigate whether the ancient communities inhabiting the Velondriake region in southwest Madagascar significantly modified their landscape in ways that persist into the present. Specifically, we hypothesize that lasting changes in vegetative communities and soil chemistry are legacies of fitness-enhancing activities that have landscape-scale effects. We further demonstrate that these legacies can be systematically characterized using remote sensing and machine learning techniques. Machine learning, specifically probability-based methods (e.g., Breiman 2001; Malley et al. 2012), allow us to systematically evaluate the likelihood of anthropogenic disturbance across large geographic spaces based on the geophysical properties identified in remotely sensed data. We look at geophysical properties of vegetation and soil as a palimpsest resulting from movement, settlement, and resource use over thousands of years. We then compare these landscape signatures between locations with and without material culture surface scatters to assess cumulative anthropogenic effects on the landscape. Our expectation is that places where people settled or engaged in sustained land-use will exhibit significantly different patterns in vegetative and soil properties when compared to locations with no evidence of archaeological settlement.

[Figure 2]

While the exact timing of the initial peopling of Madagascar is hotly debated (e.g., Anderson et al. 2018; Douglass et al. 2019; Hansford et al. 2020; Mitchell 2020), coastal foraging has a long history on the island (e.g., Barret 1985; Douglass 2016; Douglass et al. 2018; Dewar et al. 2013; Rakotozafy 1996), and predates evidence for the introduction of farming and herding lifeways (Domic et al. In Review; Godfrey et al. 2019; Hixon et al. 2021). The debate over Madagascar's human settlement has been central to questions of anthropogenic impact on the island, notably via activities that may have contributed to the extinction of endemic fauna (Godfrey and Douglass in press). Theories regarding anthropogenic drivers of extinction include potential overhunting, habitat modification, and forms of direct or indirect competition between endemic and introduced animals (Burney 1997; 1999; Robert E. Dewar 1984; 1997; Godfrey et al. 2019; Hixon et al. 2018). Teasing apart drivers of extinction requires further clarification of anthropogenic landscape change, including in regions with long histories of foraging and the management of wild resources. Madagascar is also known for its long history of climatic variability (e.g., Douglass and Zinke 2015; Dewar and Richard 2007). As climate change impacts intensify today, studies of how past populations modified landscapes to mitigate the impacts of resource scarcity and climate variability are vital for promoting sustainability (Douglass and Cooper 2020; Douglass and Rasolondrainy 2021; Razanatsoa et al. in press). However, most archaeological sites that retain information about resource use and adaptation by early mobile communities of foragers and herders consist of ephemeral artifact surface scatters and are actively disappearing due to erosion and development (Parker Pearson 2010; Davis, DiNapoli, and Douglass 2020). Innovative approaches are thus particularly needed to clarify human-environment dynamics during the earliest phases of Madagascar's human settlement and in regions vulnerable to loss or erosion of cultural landscapes.

2 Niche Construction and the Legacy of Land-Use Practices

Anthropologists interested in the effects that humans have on their environment and the two-way feedbacks in socio-ecological systems have productively integrated Niche Construction Theory (NCT) (Fuentes 2016; Laland and O'Brien 2010; Zeder 2016). NCT, which stems from evolutionary biology, stresses that organisms actively modify the selective pressures in their environment in order to increase their fitness. In doing so, all organisms contribute to feedbacks that influence and alter the niches of other organisms that share those same spaces (Laland and O'Brien 2010; Odling-Smee, Laland, and Feldman 2003). It should be emphasized that many of the concepts of NCT borrow from related concepts previously described by evolutionary biologists (see Spengler 2021), such as environmental engineering (e.g., Jones, Lawton, and Shachak 1994; Jones et al. 2010) – central to the work presented here. NCT has guided investigations of how "low impact" human activities create niches by altering the distribution and abundance of flora and fauna in ways that enhance human livelihoods (Rowley-Conwy and Layton 2011). Prior work shows that many such niche construction activities are identifiable through soil changes (Smith 2001) and alterations to vegetation (e.g., modification of trees) (Mobley and Eldridge 1992; Oliver 2007). Investigations of cultural landscapes further demonstrate how humans intentionally manipulate soil chemistry and vegetative growth patterns (Lightfoot et al. 2013). Such niche construction activities have landscape-scale effects that are difficult to assess using site-based approaches alone. Furthermore, taphonomic processes and other destructive forces can disproportionately affect the remains of ephemeral sites (i.e., foraging camps) and evidence for landscape management by "low impact" communities with high levels of mobility (Iovita et al. n.d.; Smith 2001). Applications of NCT and related evolutionary frameworks to landscapes shaped by foraging economies have also revealed feedbacks between human use of fire, biodiversity, and resilience to climate change (Bliege Bird et al. 2008, 2020; Bliege Bird and Bird 2020; Bird et al. 2016). This work demonstrates the vast spatial extent and persistence through time of legacies of landscape management by foragers, including through innovative use of historical aerial photographs that permit landscape-scale analysis of the effect of previous fire regimes on contemporary settlement and land-use patterns (Bliege Bird et al. 2020).

Our paper aims to build on this previous work by combining archaeological satellite-based remote sensing and innovative computational automation approaches to reveal legacies of forager land-use in coastal Madagascar. Prior remote sensing studies of archaeological foraging societies (and recently paleoanthropological sites) have taken place around the world, and many have relied on unsupervised land-cover classifications and environmental proxies to narrow down survey areas to where ephemeral cultural deposits are likely to exist (Coelho, Anemone, and Carvalho 2021; Davis et al. 2020; Keeney and Hickey 2015; Lim et al. 2021). Here, we attempt to use multispectral satellite data to directly pinpoint ecological changes associated with archaeological activity. Innovating and expanding the use of approaches that can effectively reveal "low-impact" signatures of human-environment dynamics is critical for developing more holistic understandings of the contributions of diverse communities—including highly mobile foraging communities—to shaping landscapes (Crumley 1979).

In leveraging NCT, we are also engaging principles of relocation and perturbation (Figure 3), wherein relocation refers to the movement of certain ideas and resources, and perturbation refers to the subsequent adaptation and changes to both human populations and environments over time (Odling-Smee, Laland, and Feldman 2003; Quintus and Cochrane 2018). Signatures of a modified niche include changes to biotic, abiotic, and artifactual components of the environment, and must be related to intentional, non-random processes (Odling-Smee et al. 2013; also see Jones et al. 2010). In order for remote sensing tools to identify niche construction, we must be able to recognize instances of both perturbation (to quantify landscape modifications, themselves) and relocation (to identify different kinds of niche construction and the potential movement of people across a landscape). Relocation and perturbation should be traceable via similarities in material culture between sites, but also via patterns in vegetative and soil properties; i.e., archaeological niche construction will display perturbations in the form of distinct geophysical characteristics related to vegetative and soil characteristics and these differences will be relocated as communities migrate between places.

[Figure 3]

In this study, we focus primarily on perturbation effects. Relocation will be the focus of future work and will require a robust radiocarbon dataset to evaluate settlement chronologies and temporal shifts in settlement. Nonetheless, our present study has ramifications for how archaeologists reconstruct and understand the impacts of foraging societies on a global scale, as the methods proposed here can be widely applied. It also contributes new insights into longstanding questions regarding the consequences of human colonization of the unique insular environments of the southwestern Indian Ocean, and Madagascar specifically.

3 Methods

Previous studies, using traditional ground-based and remote sensing survey (Davis et al. 2020; Davis, DiNapoli, and Douglass 2020; Douglass 2016), have expanded our understanding of Late Holocene

(~3,000 cal year B.P.) settlements on Madagascar's southwest coast. This work assessed whether settlement was affected by resource availability and used satellite-derived information about environmental factors (e.g. proximity to important resources) to generate a probability model to locate archaeological settlements. This work documented hundreds of new archaeological deposits and indicated that freshwater availability, marine resources, and defensibility are among the primary drivers of settlement choice and mobility in this region since the Late Holocene. Additionally, this work suggested the presence of Allee effects, or positive density dependence, wherein settlement actively modifies surrounding environments and results in improvements to habitat suitability (Fretwell and Lucas 1969; Angulo et al. 2018).

In this paper, we are addressing whether ecological legacies of landscape modification exist and whether these constructed niches—primarily in the form of soil and vegetative properties—can allow us to predict ancient settlement locations and provide insight as to the extent of anthropogenic landscape modifications (Figure 1). In order to do this, we must first determine whether available satellite data have the spectral resolution needed to discern between known archaeological sites and places that do not contain material culture deposits (Figure 1). We use high-resolution PlanetScope satellite imagery (Planet Team 2020) with 3m spatial resolution and multispectral capabilities to calculate vegetative productivity and soil moisture content in surveyed areas with known archaeological sites (n = 340). In total, we averaged 6 PlanetScope images taken between 2018 and 2020 during the wet and dry seasons to create a 3-year average of the study region (Supplemental Table 1). The years chosen experienced climatic conditions within the typical range for the region ("Andavadoaka Monthly Climate Averages" n.d.). We supplemented PlanetScope images with multispectral bands available from Sentinel-2 to provide additional assessment of moisture retention properties of soils and vegetation (see below). We then compared these values with ground-tested locations without any evidence of archaeological materials based on absence of surface deposits (i.e., ceramics, shells, charcoal, etc.; n = 80). Sites in this region tend to feature single occupation horizons and relatively shallow cultural deposits that are typically indicated by the presence of surface scatters (Douglass 2016). All archaeological and non-archaeological datapoints were recorded during systematic survey operations between 2011 and 2020 (Davis et al. 2020; Douglass 2016).

[Figure 3]

3.1 Machine Learning Algorithm

We used PlanetScope imagery and compiled 3-year averages for the dry and wet seasons between 2018 and 2020. Seasonal differences are extreme in this region (Jury 2003), and thus we need to account for these variations and how they affect our ability to discern archaeological materials in satellite data. As such, we conducted a pixel-by-pixel comparison in R (R Core Team 2020) between the 3-year averaged PlanetScope images to highlight differences in environmental geophysical properties between the wet and dry season using the equation:

$$\Delta_r = D - W$$

Where Δ_r = difference between images, D = the dry season image, and W = the wet season image.

Next, we assessed the spectral characteristics of a sample of known archaeological (n = 340) and non-archaeological (n = 80) deposits throughout the study area to determine their degree of separability between different image bands. Some prior studies have chosen non-archaeological sites randomly, but here we used ground-tested locations to alleviate potential errors in sample creation (Sonnemann et al. 2017). We drew 10m buffers around each data point and the average value for each band was calculated in R (R Core Team 2020). Then we statistically compared archaeological and non-archaeological sites using different bands of PlanetScope imagery (see Supplemental Files).

Next, we used Google Earth Engine (GEE; Gorelick et al. 2017), following Orengo et al. (2020), to train a random forest (RF) probability algorithm to identify archaeological deposits in southwest Madagascar. Because the archaeological deposits in this area are primarily ephemeral artifact scatters, high resolution data are required to attempt any sort of automated identification. We ran a RF probability algorithm using 128 trees and three iterations (which were deemed optimal for archaeological purposes by Orengo et al. (2020)) to locate artifact scatters (code can be found in the supplemental documents). The RF procedure outputs a raster of values ranging from 0-1, wherein 1 is a perfect match to an archaeological deposit. To evaluate accuracy and performance of this model, we withheld 40 archaeological points and 17 non-archaeological points (~12% of the training data) for validation. Then we calculated the precision (Equation 1), recall (Equation 2), and F1 (Equation 3) scores for the training and test data using thresholds of 0.60, 0.65, and 0.70.

$$\textbf{Precision} = \frac{\textbf{True Positives}}{\textbf{True Positives}+\textbf{False Positives}} \quad (1)$$

$$\textbf{Recall} = \frac{\textbf{True Positives}}{\textbf{True Positives}+\textbf{False Negatives}} \quad (2)$$

$$\textbf{F1} = \frac{2 \times \textbf{Precision} \times \textbf{Recall}}{\textbf{Precision}+\textbf{Recall}} \quad (3)$$

A perfect result would have precision, recall, and F1 scores of 1.

3.2 Vegetative Indices

To evaluate ecological signatures between archaeological and non-archaeological areas, we used vegetative indices, which are mathematical formulas that provide indications of biomass and plant health/stress. First, we measured vegetative productivity using normalized difference (NDVI) and soil adjusted (SAVI) vegetative indices (Jensen 2007). NDVI is calculated using the formula:

$$\boldsymbol{NDVI = \frac{NIR - RED}{NIR + RED}}$$

SAVI is calculated using the formula:

$$\boldsymbol{SAVI = \frac{NIR - RED}{NIR + RED + L} * (1 + L)}$$

Where L is a soil adjustment factor. An optimal value for L has been demonstrated at L=0.5 and was used here (Huete 1988).

NDVI is one of the most commonly employed vegetative indices and measures vegetation based on a ratio of reflectance values in the near infrared (NIR) and Red wavelengths. However, NDVI has accuracy issues when faced with ecologically and geologically heterogeneous areas and high soil reflectance. The SAVI is an adjusted version of NDVI which corrects for reflectance caused by soil diversity, making it useful for geographically expansive studies with high rates of ecological diversity (Huete 1988). Both NDVI and SAVI relay information pertaining to water absorption and retention in vegetation. After calculating vegetative index values, we extracted the average values from a 20m buffer around each archaeological and non-archaeological datapoint used for training the RF algorithm (discussed above). Then we assessed the difference between archaeological and undisturbed locations using non-parametric tests of association (see supplemental file). We conducted all calculations in R v. 4.0.2 (R Core Team 2020) using the *raster* (Hijmans 2019) and *rgdal* (Bivand, Keitt, and Rowlingson 2019) packages.

Next, we evaluated Sentinel-2 imagery, which contains short-wave infrared (SWIR) bands, in the same manner as described above. We compiled 5 years of Sentinel-2 imagery by month using GEE (Gorelick et al. 2017; also see Supplemental Files). SWIR has increased sensitivity to moisture content and can be used to distinguish mineral compositions of soils (Thabeng, Merlo, and Adam 2020; Davis 2017). One limitation of the Sentinel-2 data is that it has much lower spatial resolution (20m). The only high-resolution SWIR satellite currently available is Maxar's Worldview-3 satellite (which has shown promise for archaeological purposes, see Davis 2017). We did not have access to these particular data, however. To improve the utility of the Sentinel-2 SWIR, we used a pansharpening procedure – a form of data fusion whereby lower-spatial resolution imagery is enhanced using a higher-resolution dataset (Garzelli et al. 2004) – to resample the SWIR data from 20m to 3m using PlanetScope imagery (see Supplemental Figure 1). Pan-sharpening followed a principle-component analysis (PCA) method using the RStoolbox package in R (Leutner, Horning, and Schwalb-Willmann 2019). PCA pansharpening is appropriate because PlanetScope imagery is spectrally compatible with Sentinel-2 sensors (Ichikawa and Wakamori 2018).

Using this pansharpened SWIR data, we calculated a Normalized Difference Water Index (NDWI; Gao 1996), which is a vegetative index that reflects the biochemical metrics of plants (Sun et al. 2019). Such metrics can be used to distinguish different taxa, in addition to assessing the water content of leaves (Gao 1996; Sun et al. 2019). NDWI uses the NIR and SWIR spectrum to measure the liquid water molecules contained within vegetative canopies (Gao 1996). It is calculated using the formula:

$$\boldsymbol{NDWI = \frac{NIR - SWIR1}{NIR + SWIR1}}$$

Where NIR is the near-infrared band and SWIR1 corresponds to the first shortwave-infrared band of Sentinel 2 (1610 nm).

Finally, to assess the potential bias in our samples of archaeological and non-archaeological points, we generated 1000 random points within the study area and compared vegetative index and SWIR reflectance values between them and our ground-tested data (Supplemental Figure 2). If people have fundamentally changed the geophysical and/or geochemical properties of the landscape, we hypothesized earlier that the random locations will express different vegetative and soil properties than areas with archaeological surface scatters. Conversely, if people merely settled in areas with specific geochemical characteristics that are distributed throughout the landscape, random locations should show some similarities with archaeological areas.

3.3 Spatial Analysis

In order to quantify the impact of niche construction on different parts of the study area, we ran several spatial analyses to determine the amount of land area impacted by legacy effects and the distribution of niche construction activities across the landscape. Settlements in this region are non-randomly distributed (Davis, DiNapoli, and Douglass 2020), as are niche construction activities more generally (Odling-Smee et al. 2013). Thus, anthropogenic niche construction on Madagascar should also be non-random, and likely clusters in particular places that have been used repeatedly over time. After assessing the results of the RF algorithm, the locations identified as archaeological sites with the threshold with the highest accuracy scores were converted to polygons. We calculated the area of these polygons to generate an assessment of the extent of archaeological activity within the study region. Next, we analyzed the spatial distribution of these points using the Getis-Ord General G test to compare the distribution of areas identified as archaeological by the RF algorithm with random patterns (Getis and Ord 1992). Then we converted the polygons of anthropogenic locations into points and computed kernel density estimations for these locations. We conducted all spatial tests in in ArcGIS 10.7.1 (ESRI 2020).

4 Results

Assessments of training datasets and PlanetScope imagery resulted in clear distinctions between archaeological and non-archaeological points in all four electromagnetic bands (Blue, Green, Red, NIR; Figure 4b). The differences between the samples are also statistically significant (see Supplemental Files). The RF classifier was trained using 300 archaeological points and 63 non-archaeological points and resulted in strong performance on both the training data and test data (see Table 1; Figure 4).

[Figure 4]

Analyses of annually averaged NDVI and SAVI show a significant difference ($W = 8639$, $p < 0.05$) between vegetation in archaeological and non-archaeological contexts, where archaeological sites have higher mean vegetative index values than locations without archaeological activity (Figure 5; mean of -0.02 and -0.03, respectively). NDWI results show the same pattern ($W = 8468$, p-value = 0.042). This suggests that archaeological sites exhibit vegetative index values that are distinct from non-archaeological areas. Furthermore, archaeological sites are noticeably different in their vegetative index value distribution from randomly generated points throughout the study region (see Supplemental Figures. 2 – 5).

[Figure 5]

SWIR analysis indicates that there is a tendency for areas surrounding archaeological sites to have slightly higher reflectance values in the SWIR spectrum (SWIR1: $W = 12713$, p-value > 0.002; SWIR2: $W = 11999$, p-value = 0.024). Most archaeological deposits express higher reflectance in the SWIR spectrum, indicating mineralogical differences and vegetation that might be distinct from surrounding non-archaeological areas.

Seasonally, we find that NDVI and SAVI values during the wet season, show a significant difference ($W = 8282$, $p < 0.02$) between vegetation in archaeological and non-archaeological contexts, where archaeological sites have higher mean vegetative index values than locations without archaeological activity (mean of -0.005 and -0.008 respectively; see Supplemental Figure 2). During the dry season, however, there is no significant difference (W = 10230, p = 0.925) between locations.

Using the RF results with a threshold of 0.65, we calculated the area of all identified potential archaeological deposits within the study region. Approximately 38.6 km^2 (~17%) of the study region exhibits differences in soil and vegetative properties which are likely linked to human activities. Spatial analyses demonstrate that anthropogenic areas are clustered and non-randomly distributed throughout the landscape ($p > 0.0001$; Supplemental Figure 6). The density of anthropogenic areas appears highest 3-5km inland from the coast (Figure 6), where there are known to be an abundance of seasonal freshwater ponds.

[Figure 6]

5 Discussion

The results of this analysis suggest that ancient coastal communities in southwest Madagascar – including highly mobile foraging and herding populations – have contributed to shaping the modern landscape in important ways. Our previous work contributed directly to this present study by allowing us to investigate settlement patterns and landscape change from two different, but complementary, angles. Our prior investigations focused on the factors that influence settlement choice (e.g., resource availability and social cohesion), while this study focuses on the long-lasting, landscape-scale effects of settlement. In fact, prior work (Davis et al. 2020; Davis DiNapoli, and Douglass 2020) indicated the presence of Allee effects, which suggests that ancient communities actively modified their ecological surroundings in ways that increased the suitability of previously settled areas. Here, we used machine learning and vegetative indices to further investigate the possibility that Allee effects were present in coastal Madagascar and resulted in legacy effects via cultural niche construction. The results of this study largely complement earlier investigations, pinpointing specific areas that contain landscape modifications, many of which overlap with previous predictive modeling results (Figure 7). Archaeological deposits exhibit significantly different spectral characteristics when compared to non-archaeological locations. While the potential of multispectral and hyperspectral imagery has long been established for archaeology, the detection of scant artifact scatters is not the norm (c.f., Orengo and Garcia-Molsosa 2019). Rather, most literature focuses on the detection of highly visible landscape modifications, like architecture and remains of intensive agricultural activity (e.g., Tarolli et al. 2019; also see Davis 2021). As such, this work suggests that the development of machine learning and cloud-based computational processing provides the ability to detect even the most ephemeral archaeological deposits and use these to reveal patterns of human activity and impact on the wider landscape.

[INSERT FIGURE 7]

Our analysis shows that the overall health and abundance of extant vegetation (defined by vegetative index scores) on and around archaeological deposits exhibits a statistically significant different when compared to areas lacking any archaeological materials. The exact difference is not clear, however, as assessments of median values suggest vegetative values are higher in non-archaeological locations while evaluations of mean values suggest that vegetative values are higher in archaeological locations. The contrast between these two averages may be indicative of the wide range of environmental contexts within the study area and could suggest that non-archaeological localities exhibit wider range of environments while archaeological areas are more limited in their vegetative diversity. This, itself, could be the result of active settlement choices or the effects of human landscape modification. This hypothesis is supported by Figure 5, which shows a larger range of values among non-archaeological areas compared with archaeological locations.

The difference in vegetative index scores is statistically significant in the wet season ($p = 0.01$). Additionally, the SWIR wavelength displays differences in the soils around archaeological sites and non-archaeological locations, suggesting that there are underlying differences in the mineralogical composition and moisture retention properties between areas with and without archaeological surface materials. NDWI index assessments further demonstrate that areas with archaeological materials have vegetation with different water retention properties than non-archaeological or random locations. This may signal healthier vegetation, overall, or might relate to the presence of introduced taxa that are not xerophytic and thus retain more water than endemic taxa. Because this region is arid and rainfall is highly variable (Jury 2003), even small increases in vegetation moisture content could have significant implications for human livelihoods and the biota that sustain them. This, coupled with spatial tests of identified archaeological deposits, indicates the presence of a distinctive human niche on Madagascar resulting from a variety of economic activities – ranging from foraging to pastoralism and agriculture – since the Late Holocene. The inland areas of the study area may have been preferred by pastoralists who have been present for the past several hundred years (Parker Pearson 2010), and the anthropogenic signatures found here may therefore reflect the activities of pastoral and foraging community activities. While the precise geochemical composition of soils requires further ground-based studies, human activity has likely played a role in changing these components of the landscape.

Some caution is necessary in interpreting these results, however. While it is possible that these distinctive differences between archaeological and non-archaeological locations are due to human activities (e.g., Storozum et al. 2021), it is also possible that these soils were inherently different prior to human occupation. Our prior work demonstrates that human settlement choice is not random in this region (Davis et al. 2020; Davis, DiNapoli, and Douglass 2020), and thus communities may have chosen areas already possessing specific soil and vegetation properties. To definitively establish the nature of human impact on soil chemistry, and to understand the feedbacks between soil and vegetation dynamics in this region, future studies will need to evaluate stratigraphic and geochemical changes in soil composition through time at archaeological and non-archaeological localities. This will involve ground-based survey as well as a program of radiometric dating to improve settlement chronologies.

Nonetheless, based on this analysis, we can definitively state that archaeological deposits in southwest Madagascar have distinct geophysical and vegetation profiles compared with non-archaeological locations. Likewise, the difference in vegetation between archaeological and non-archaeological areas is inherently linked to the geochemical properties of these locations, as well as to modern ecological variables. Because the primary difference between our study locations is the presence or absence of archaeological deposits, vegetative differences are likely linked to human activity (Lasaponara and Masini 2007; Bennett et al. 2012). Furthermore, our results indicate that ephemeral archaeological deposits composed of artifact scatters can be distinguished from surrounding environments using high-resolution multispectral imagery and machine learning. Thus, we can conclude that underlying differences in geophysical properties of the landscape and vegetative composition are impacted by a legacy of human landscape use over the past several thousand years. The results presented here demonstrate that archaeological sites dated to as early as ca. 3000 cal year B.P. by Douglass (2016) are identifiable based on their ecological impact. However, a robust settlement chronology for the study region is needed to investigate whether the age of archaeological deposits impacts their signature or detectability via multispectral remote sensing.

More broadly, we demonstrate how a focus on areas with "low-impact" human activities can facilitate greater understanding of the extent of human occupation and land-use on a landscape shaped by diverse socioeconomic systems and exhibiting an ephemeral archaeological record (Douglass and Zinke 2015; Parker Pearson 2010). The impacts of early communities of foragers on Madagascar's diverse ecosystems is widely debated, but more evidence of the (in)direct effects of human settlement are needed (Davis et al. 2020; Domic et al. In Review; Douglass et al. 2019). The same can be said for many regions around the world where the availability and quality of archaeological data is lower for periods of time when foraging was the dominant livelihood strategy shaping landscapes (Stephens et al. 2019). By extending our focus to these understudied components we can re-evaluate and more fully appreciate the extent to which diverse peoples have modified the Earth's environments.

A shift in research attention toward understanding the environmental impacts of small-scale and mobile subsistence communities can also fundamentally change how we approach sustainability and conservation. One of anthropology's longstanding goals has been to understand the dynamics between human and environmental systems (Davis 2020; Steward 1955; Carneiro 1970; Steward and Setzler 1938). Long-term perspectives on human-environment dynamics offered by archaeology provide context for understanding contemporary land-use and sustainability issues. A goal of historical ecology and ecological anthropology is to derive lessons from these long-term perspectives and eco dynamics to inform present and future management decisions (Altschul et al. 2017; 2020; Rick and Sandweiss 2020). By viewing anthropogenic landscape modifications at multiple scales and levels of intensity, as well as via a range of (in)direct impacts, we can improve our understanding of human niche construction in diverse societies, ranging from small-scale, mobile communities to large urban centers.

This paper makes contributes to Malagasy archaeology by illuminating the scale and extent of human traces on the landscape, in a way that is time and cost-effective, allowing us to lay the critical foundation needed for further work on coupled human-natural systems. The archaeological data contained within this space has implications for our understanding of human niche construction on Malagasy landscapes over time. Beyond Madagascar, this study also holds importance for studying the ecological legacies of foraging societies and detecting ephemeral archaeological sites in semi-arid environments using high resolution satellite images and machine learning techniques.

6 Article types

Original Research

6.1 Figures

Figure 1: Illustrates the methodological workflow presented in this article. The central question of human settlement and mobility patterns has been investigated previously by Davis et al. (2020) and Davis, DiNapoli, and Douglass (2020) as a consequence of resource availability and social aggregation. The results of this prior work feed directly into this article, and vis versa (indicated by dashed arrow). Within this paper we evaluate whether we can distinguish between archaeological and non-archaeological areas recorded in our previous work based on spectral properties (including

vegetative indices). Then, we use these results to train a machine learning classifier to quantify the extent of anthropogenic impacts.

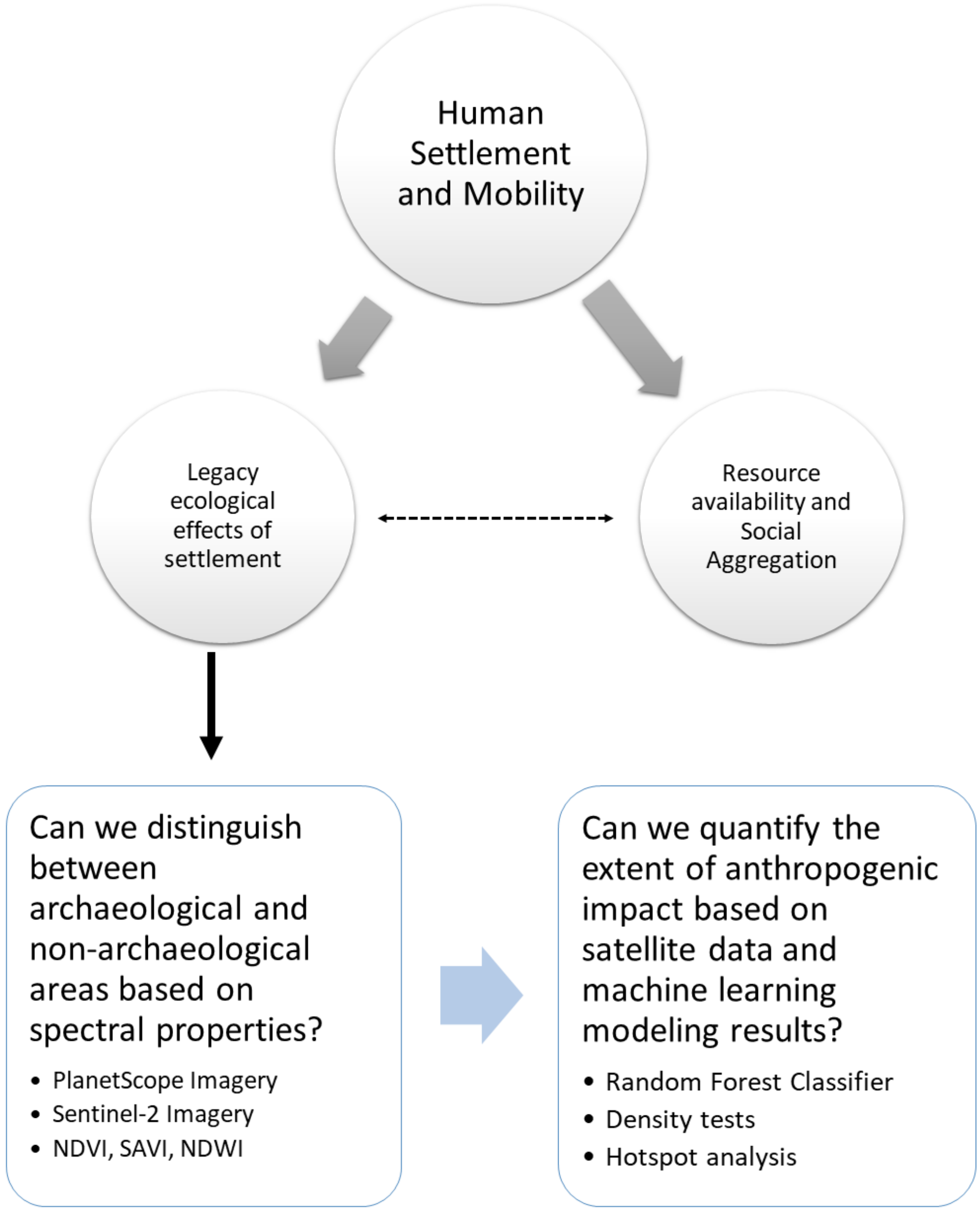


Figure 2. Map of the study region (white box).

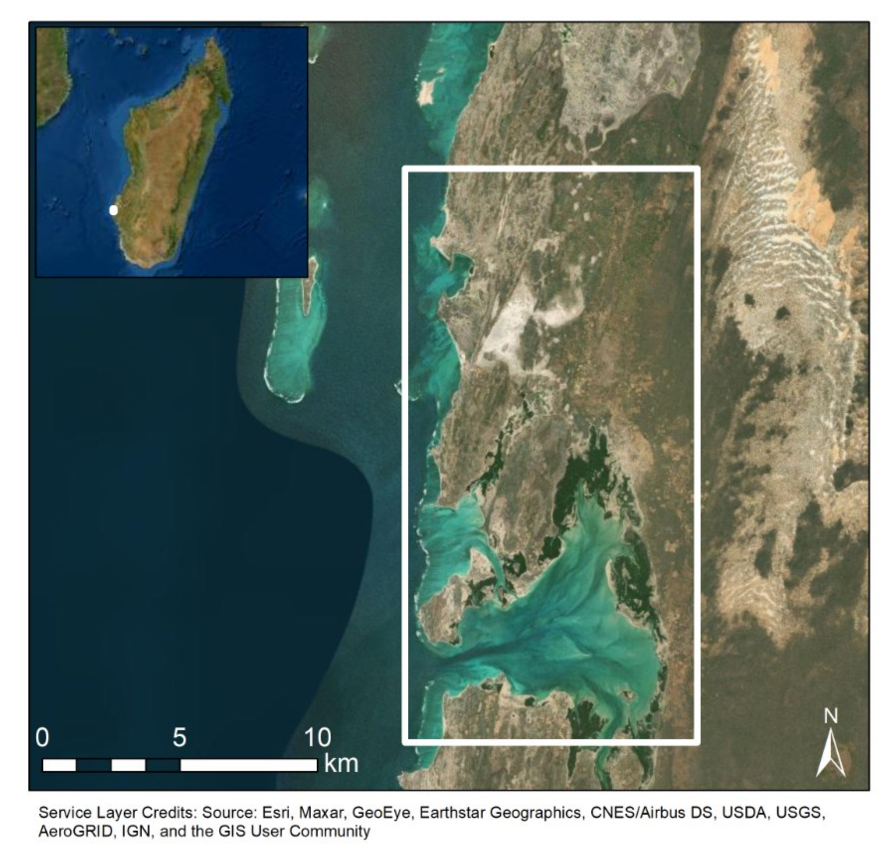


Figure 3. Illustration of perturbation and relocation components of NCT. Each population (A – C) performs specific activities which create feedbacks (blue arrows) between themselves and their surrounding environments. This constitutes a cultural "niche". Relocation is represented by the dashed arrows, in which people move throughout a landscape and take their practices with them. In addition, ideas and adaptations can be spread from one community to another (gray circles) when different groups overlap in time and space, leading to the adoption of new behaviors and the formation of new niches (A' – C').

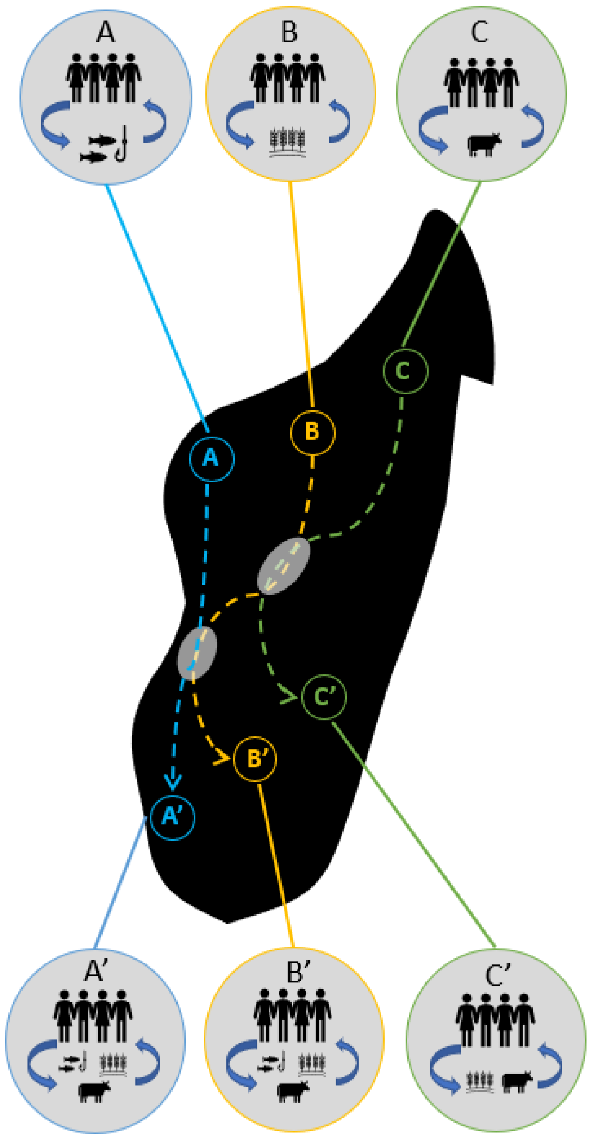


Figure 4. ***A:*** Results of RF algorithm (red) using a threshold of 0.7 compared with known archaeological deposits (yellow circles) and non-archaeological areas (green circles). ***B:*** Visualization of band separability between archaeological and non-archaeological training data. All band differences are statistically significant (p < 0.001). ***C:*** Close up of known archaeological and non-archaeological sites. All but one are correctly identified. ***D:*** Another area with anthropogenic activity (forest clearings indicated by arrows) and known archaeological sites. Imagery © 2020 Planet Labs. Inc.

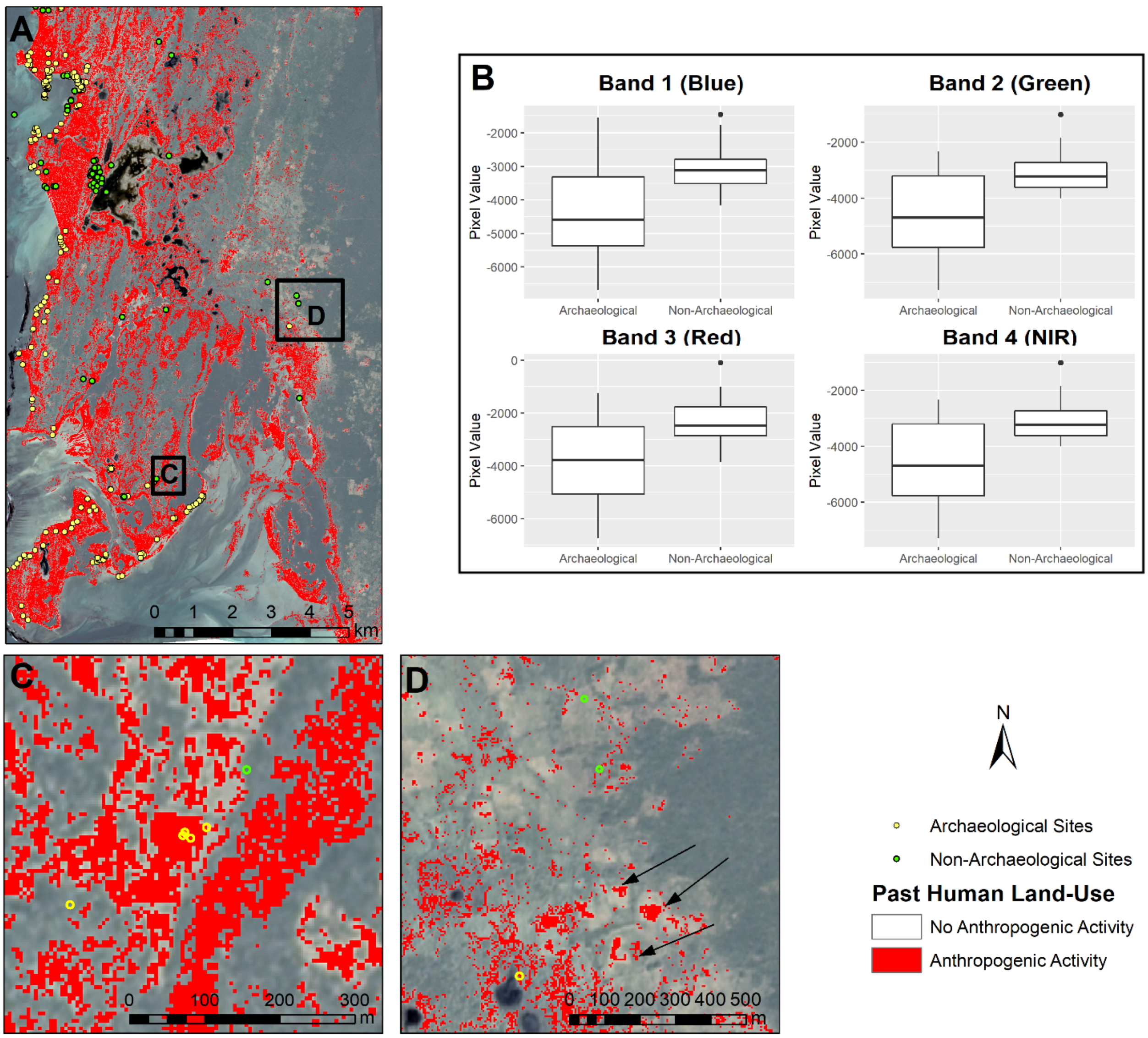


Figure 5. Vegetation index values for archaeological and non-archaeological locations. NDVI and SAVI are annual averages over 3 years of PlanetScope imagery (Planet 2020). NDWI uses the annually averaged PlanetScope and Sentinel-2 SWIR bands.

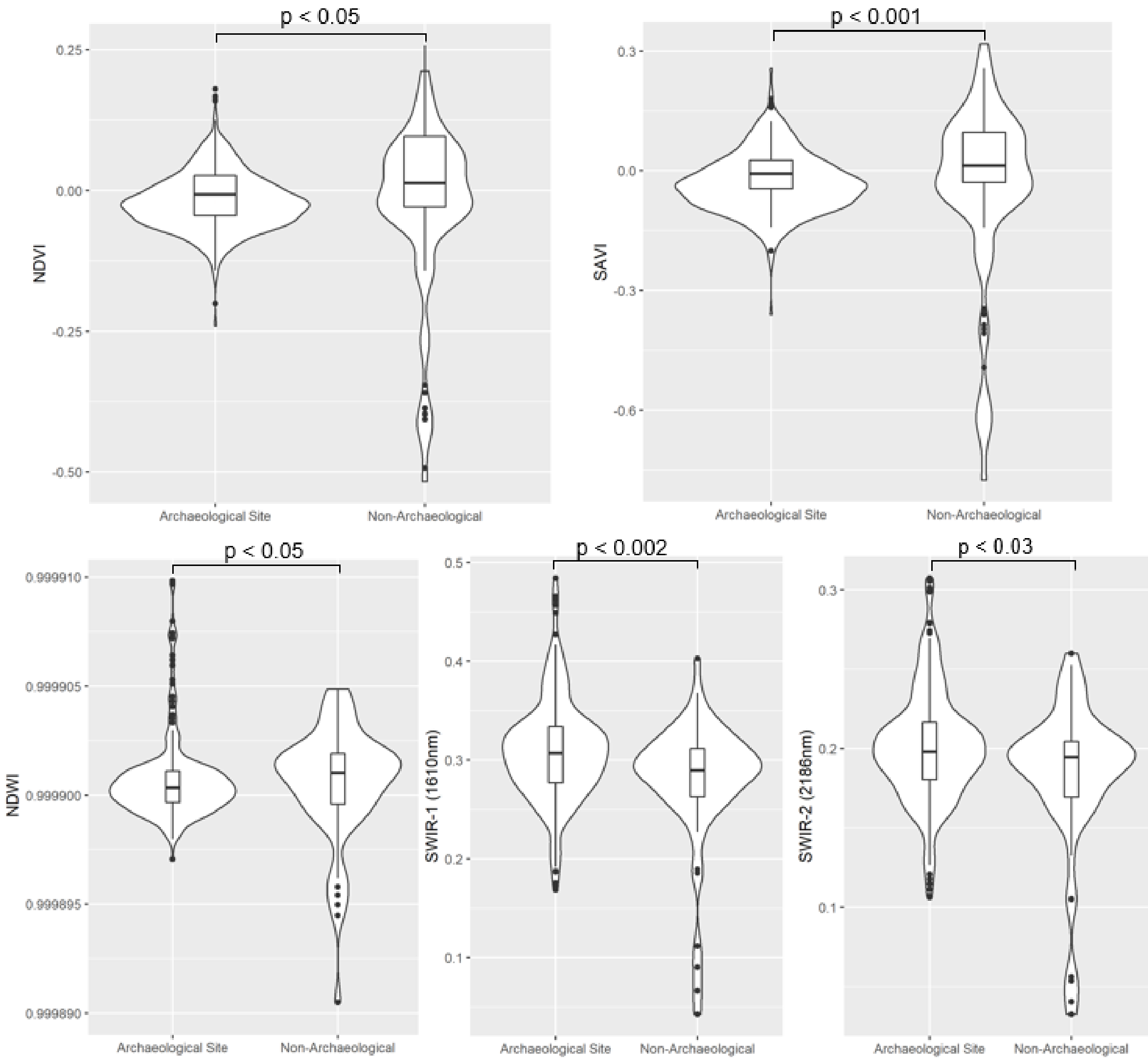


Figure 6. Density of anthropogenic modifications within the study region identified by the machine learning algorithm. Imagery © 2020 Planet Labs. Inc.

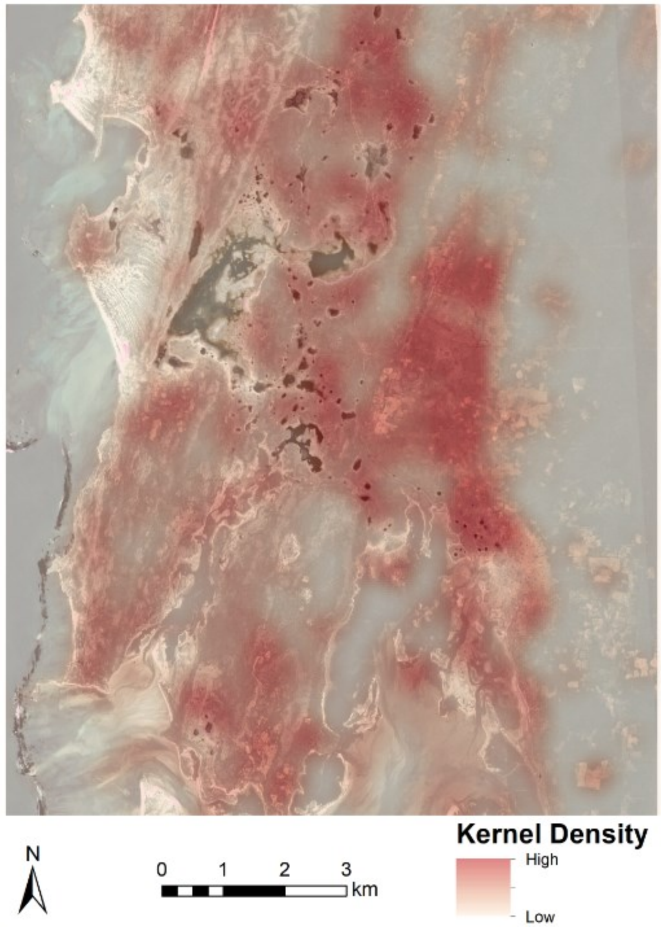
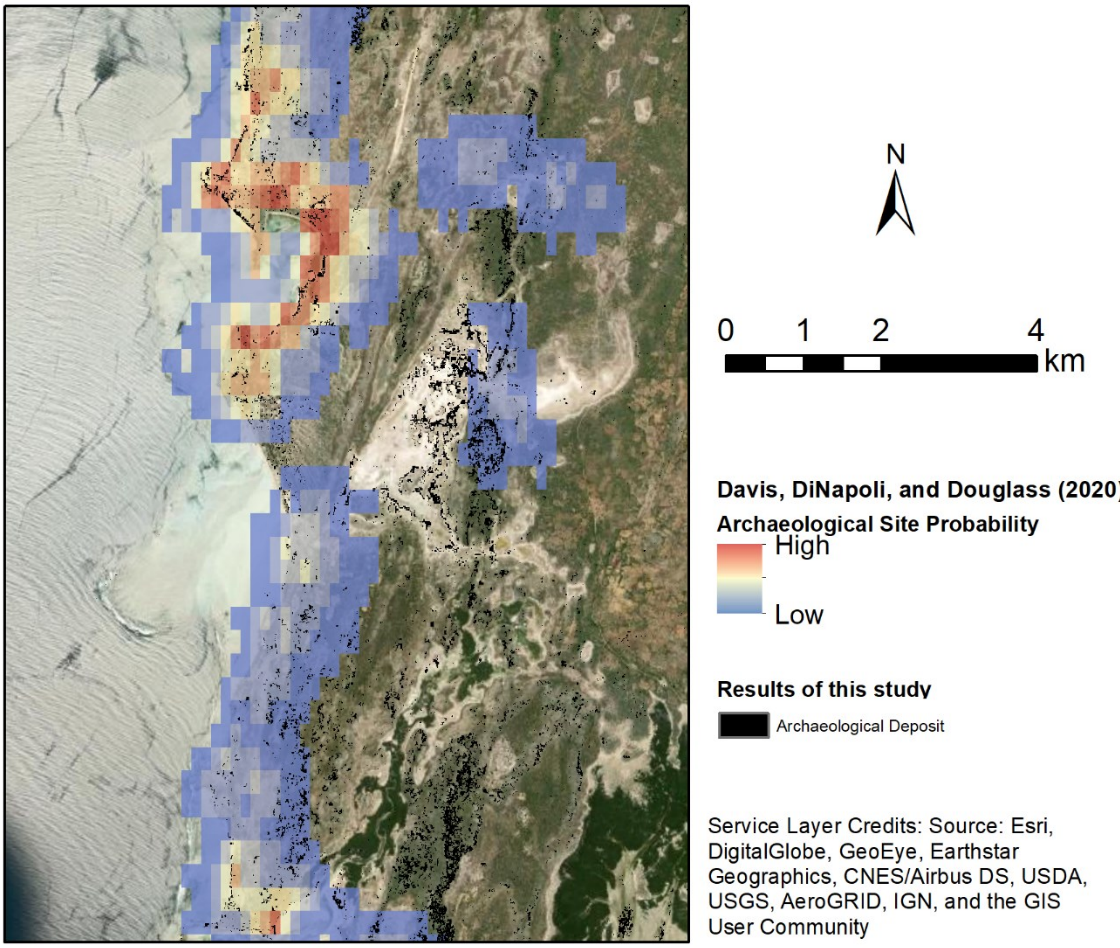


Figure 7. Comparison between predictive modeling results of Davis, DiNapoli, and Douglass (2020) and this study. The previous study investigated settlement distribution via environmental and social drivers, while this study looked at long-term ecological effects of settlement activity. Notice that both models detect or predict archaeological activity in many of the same locations. The areas ranked with the highest likelihood by Davis, DiNapoli, and Douglass (2020) also contain some of the oldest recorded evidence of human occupation in this region (~2500-3000 cal year B.P.).



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6.2 Tables

Table 1. Accuracy assessment of random forest algorithm.

Threshold	Precision (Validation)	Recall (Validation)	F1 (Validation)	Precision (Training)	Recall (Training)	F1 (Training)
0.7	0.972	0.875	0.921	0.976	0.963	0.969
0.65	0.973	0.900	0.935	0.977	0.973	0.975
0.6	0.947	0.900	0.922	0.964	0.977	0.970

7 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

8 Author Contributions

Designed research (DSD), Performed research (DSD), Analysed data (DSD, KD), Wrote and revised the paper (DSD, KD), Funding Acquisition (DSD, KD).

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12 Supplementary Material

Supplementary materials can be found in the accompanying document with this submission.

1 Data Availability Statement

The PlanetScope imagery analyzed for this study is proprietary, and unfortunately cannot be shared. However, access to PlanetScope imagery is free for educators and researchers via Planet's Education and Research Program: https://www.planet.com/markets/education-and-research/. The datasets generated from PlanetScope image analysis (i.e., density tests) for this study can be found in Penn State's ScholarSphere Repository at https://doi.org/10.26207/zmsr-tc92. Data can also be replicated using GEE. Compilation of Sentinel data in GEE can also be run using the following link: https://code.earthengine.google.com/67eeee7b0e7cb49beac1237aff1f5f53 and the Random Forest analysis can be run in GEE using the following link: https://code.earthengine.google.com/99ccb498ea588d44a0b3300841163405.